Return to

NASA CR 132361

COMPUTER PROGRAM TO PERFO[illegible] AND WEIGHT ANALYSIS OF TRANSPOR[illegible] AIRCRAFT

FINAL REPORT
VOLUME I ✦ SUMMARY

GENERAL DYNAMICS
Convair Aerospace Division

G. MUNROE

NASA CR 132361

COMPUTER PROGRAM TO PERFORM COST AND WEIGHT ANALYSIS OF TRANSPORT AIRCRAFT

FINAL REPORT

VOLUME I ✦ SUMMARY

November 1973

Submitted to
National Aeronautics and Space Administration
LANGLEY RESEARCH CENTER
Hampton, Virginia

Prepared Under
Contract NAS1-11343

Prepared by
GENERAL DYNAMICS
CONVAIR AEROSPACE DIVISION
San Diego, California

Page intentionally left blank

Page intentionally left blank

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

This report presents the results of a research and development study performed under NASA contract NAS 1-11343. The objective of this study was to develop an improved method for estimating aircraft weight and cost using a unique and fundamental approach originated by Convair Aerospace. The results of this study were integrated into a comprehensive digital computer program, which is intended for use at the preliminary design stage of aircraft development. The program provides a means of computing absolute values for weight and cost, and enables the user to perform trade studies with a sensitivity to detail design and overall structural arrangement. Both batch and interactive graphics modes of program operation are available. The report is documented in three volumes – the Final Report Summary, the Final Report Technical Volume, and the User's Manual.

The cost derivation portion of the program encompasses the areas of manufacturing and material cost, engineering cost, tooling cost, total vehicle program cost, and a return-on-investment analysis. The approach provides an accounting of aircraft weight and cost elements beginning with initial conceptual design studies and continuing through detail design, aircraft production, and flight operations. The fundamental weight and cost driver is the definition of a detail parts listing that is generated for a given vehicle when only conceptual details of a configuration are available for use as input. The detail parts from this listing are analyzed individually to determine their weight and cost. Summations are made, adding in weight and costs of assembly elements, to determine the complete vehicle weight and manufacturing cost.

The detail part level breakdown of components is attained through the use of several synthesis routines coupled in a series. A vehicle synthesis routine acts as the overall driver. The input consists of generalized vehicle and mission parameters that are typically known at the preliminary design level. This routine sizes the overall vehicle, generates major vehicle component weights, and derives a large amount of overall vehicle geometry. The output from this routine is used, in turn, to drive a structural synthesis routine that sizes, weighs, and derives geometry for major subcomponents. The detail part definition process follows, which calls out, for each of the major subcomponents specified, a list of the typical detail parts making up the subcomponent. These detail parts then represent the basis of the fundamental level for the weight and cost analysis.

The computer program is written in Fortran IV and is designed for use on CDC 6000 series computers. Several test cases, using data for existing aircraft, were run to check the program results against actual data. It was shown that

the program represents an accurate and useful tool for estimating purposes at the preliminary design state of airframe development. A sample case along with an explanation of program applications and input preparation is presented in the User's Manual volume of this report. Table 1 is a summary of the program functional capability and Figure 1 is a program block diagram.

Table 1. Summary of the Program Functional Capability

Vehicle Synthesis (Sizing)	Manufacturing Cost
Aircraft Balance	Material Cost
Mission Center of Gravity Envelope	Engineering Cost
Area Ruled Fuselage Geometry	Tooling Cost
General Curve Plotting	Total Vehicle Program Cost
Structural Synthesis	Return-on-Investment
Parts Definition and Weight	Airline Route Analysis

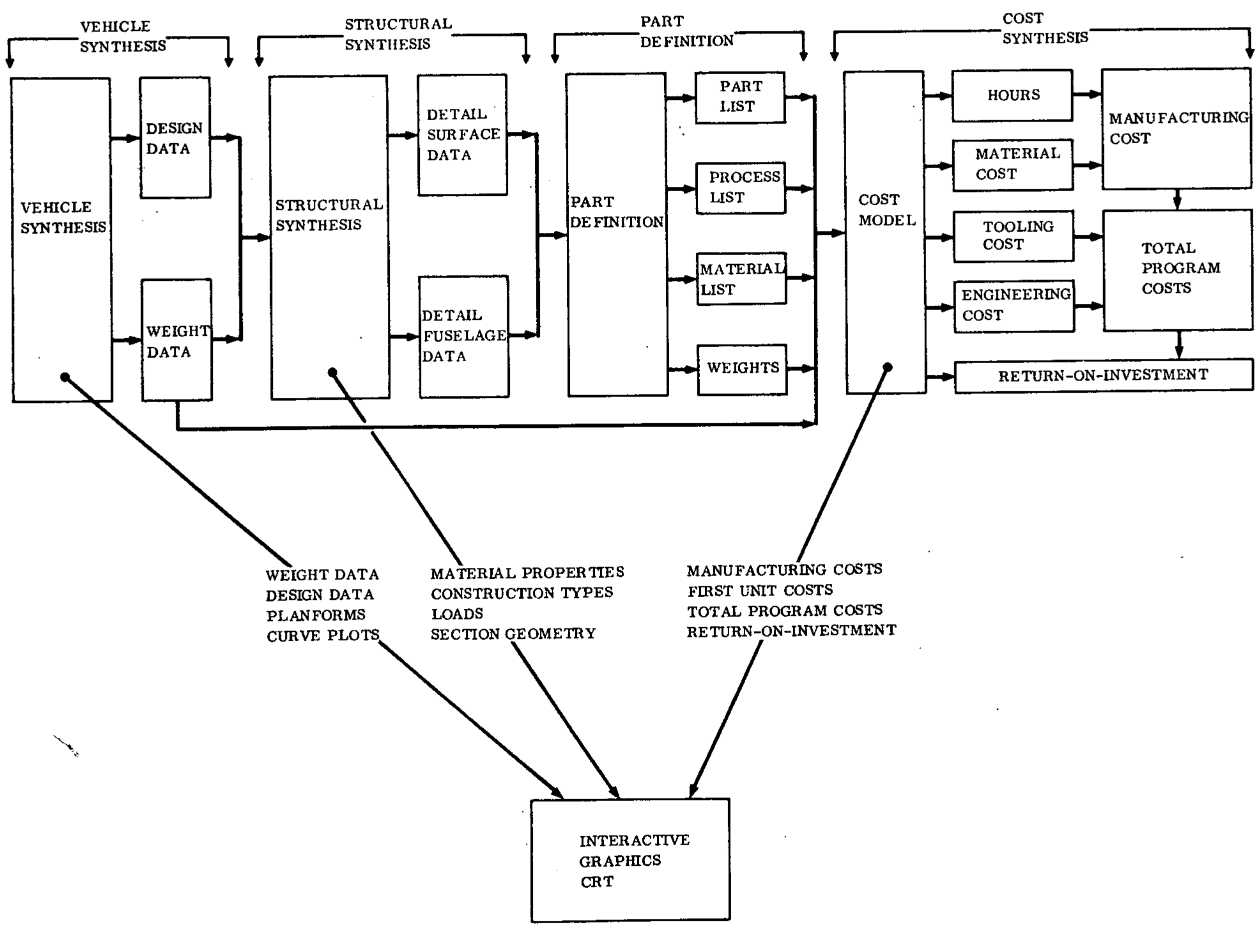

Figure 1. Vehicle Design and Evaluation Program (VDEP) Block Diagram

SECTION 1

INTRODUCTION

With the steadily rising cost of aircraft production and operation, and with the large number of materials and structural design concepts applicable to flight vehicles, it becomes increasingly important to be able to assess the impact of aircraft design alternatives in terms of cost and performance. A major deficiency of past cost-estimating methods has been the result of an over-reliance on vehicle weight as a cost driving variable. Assuming the use of conventional materials and structural methods, weight was indeed a useful parameter in cost studies. However, advances in technology have produced components of increased specific strength, and hence, decreased weight, but at the expense of requiring increasingly exotic materials and fabrication complexities. The result has been an inverse in the typical cost/weight relationship. A second deficiency of previous cost-estimating methods has been the use of oversimplified cost models that lack the depth necessary to provide a sensitivity to design tradeoff choices in terms of structural materials and methodology.

The objective of this study was to develop a digital computer program for evaluating the weight and costs of advanced transport designs. The resultant program, intended for use at the preliminary design level, incorporates both batch mode and interactive graphics run capability. The basis of the weight and cost estimation method developed is a unique way of predicting the physical design of each detail part of a vehicle structure at a time when only configuration concept drawings are available. In addition, the technique relies on methods developed at the San Diego Operation to predict the precise manufacturing processes and the associated material required to produce each detail part.

The starting point of the present effort was a computer program developed under NASA Contract NAS 2-5718, Estimation of Airframe Manufacturing Costs. The previous study was fundamental in establishing the feasibility of the methodology to be applied. Incompassing the areas of manufacturing and material cost, engineering cost, tooling cost, total vehicle program cost, and return-on-investment, the current study represents a significant extension and refinement of the methods originally formulated.

Weight data are generated in four areas of the program. Overall vehicle system weights are derived on a statistical basis as part of the vehicle sizing process. Theoretical weights, actual weights, and the weight of the raw material to be purchased are derived as part of the structural synthesis and part definition processes based on the computed part geometry.

The manufacturing cost analysis, based at the individual detail part level, is made by considering the actual manufacturing operations reuired to produce that part. A list of shop operations is called out with each detail part, and a series of equations associated with each operation is used to compute the shop hours necessary to make the part.

By applying the appropriate labor rates to the calculated hours, the direct and indirect manufacturing labor costs are found. Material costs are computed based on the amount of material required to manufacture each part.

Engineering costs are computed based on the number of manhours necessary to perform the various tasks associated with the development and production of aircraft. The computation has as its basis equations originally developed by Levenson and Barro of the Rand Corporation. Initial engineering hours are broken down and distributed among the various engineering disciplines based on studies made of historical data.

Tooling costs are computed as a function of the number of basic tool manufacturing hours, initial and sustaining aircraft production rates, and tooling labor rates. Basic tool manufacturing hours are derived as a function of the number of dissimilar parts to be produced, the average number of tools required per dissimilar part, and the average number of hours required to produce each tool.

Total vehicle program costs are computed based on a cost model that was assembled primarily from the work of Kenyon. Cost elements that are computed elsewhere in the program are brought across and substituted into the model. A learning-curve approach is utilized to derive costs of a given unit or lot as a function of the first unit cost.

A comprehensive measure of the total economic viability for a commercial transport operation is reflected in the return-on-investment analysis. Direct operating costs are computed using the 1967 Air Transport Association formula updated to 1972 cost levels. Indirect operating costs and return-on-investment are computed by applying aircraft acquisition and direct operating costs to a defined traffic structure. Output includes direct operating costs, indirect operating costs, revenue, load factors, profit, return-on-investment, and fleet size.

Great Idea

One advantage provided by the method developed is its capability to make trade studies from several levels of consideration. For example, weight and cost data can be related directly to key system parameters at the vehicle mission level such as payload, speed, range, and landing field length requirements. At the vehicle configuration level, data can be related directly to surface areas, span, sweep, taper, etc., and fuselage length, slenderness, etc. At the major component level comparisons can be made between different materials, modes of construction, detail part make-up, etc. Tradeoffs can be made to determine the overall vehicle weight and cost sensitivities at each of these levels, and in this manner the proposed aircraft design may be further and further refined down to high degree of detail. Thus, engineering functions can gain insight into the cost effectiveness of alternate aircraft systems, perform design trade studies, and perform studies to determine the impact of more detailed engineering alternatives with respect to a particular aspect of a design.

A second advantage of the method is its overall accuracy in estimating weight and cost. The increased accuracy is derived from the fundamental level of the analysis technique, starting from the detail part level. Each part and each assembly is accounted for to establish its individual effect on the cumulative total.

SECTION 2

SCOPE AND LIMITATIONS

This section briefly summarizes the scope of the study and describes some of the general limitations of the resulting computer program. The various functional areas of the study are summarized in Table 1. Following are the primary task areas requiring consideration during the course of the study.

a. Development of an aircraft balance analysis and associated graphic displays.

b. Development of a fuselage area distribution analysis and associated graphic displays.

c. Development of parts list and sizing analysis associated with aerodynamic surface secondary structure.

d. Development of an analysis for fuselage secondary structure weight and cost penalties.

e. Development of an engineering cost analysis.

f. Development of a tooling cost analysis.

g. Development of a total vehicle program cost analysis.

h. Development of an airline operational cost and return-on-investment analysis.

i. Expansion of existing standard hour computation and material cost analysis procedures to account for additional detail parts and advanced composite structural arrangements.

j. Design of the input and output interfaces between program modules, and the data storage and retrieval logic for use between program steps.

k. Programming of the communication logic between program modules and physical coupling of the program modules.

l. Design and programming of the interactive graphics displays, plotting, and change routines.

m. Overall program debugging and testing.

During the course of the program development, circumstances occasionally arose where it was necessary to make a choice between math models that incorporated some reflection of the vehicle type, e.g., fighter or transport. The tendency was to decide on analysis procedures that most closely represented a typical transport aircraft. The specific areas that are directed more toward a transport aircraft than towards other types are outlined in the User's Manual provided with this report.

Probably the greatest weakness of the resulting computer program is the lack of experience in its use. Program modules were checked out individually prior to their incorporation into the overall program, and several test cases were run through the complete program. However, to establish a high degree of confidence in the program output, a large number of test cases must be run, checked, and documented. Only in this way can the program be refined for maximum reliability and accuracy. Specific areas in which the depth of analysis or the analysis techniques might be extended or improved are discussed in detail in Section 5 of this report.

SECTION 3

TECHNICAL DISCUSSION

The essential features exhibited by the resultant weight and cost analysis program can be categorized into three major areas: the vehicle synthesis, structural synthesis, and cost synthesis. The vehicle synthesis provides overall vehicle size, balance, and dimensional data. The structural synthesis provides component and subsystem sizing, and part definition data. The cost synthesis provides manufacturing, material, engineering, tooling, and total vehicle program costs, and a return-on-investment analysis.

The vehicle synthesis process provides a rapid means of initially sizing the vehicle to derive overall vehicle geometry, weight, and balance. Input requirements are at a level typically available at the preliminary design stage of aircraft development. Output, which acts as a driver for the structural synthesis routines, is comprised of a group weight statement, group cg statement, vehicle geometry data, loads data, wing station data, engine data, landing gear data, and a mission cg range display. A detailed technical discussion, including the equations utilized within the vehicle synthesis routines, is presented in Section 2. 1 of Volume II.

The structural synthesis process provides detailed geometry, loads, and weight data for the primary structural elements associated with the aerodynamic surfaces and the basic fuselage structural shell. The synthesis utilizes a multistation analysis approach that assumes a reasonable structural continuity and a well defined elastic axis. The aerodynamic surface leading edge, trailing edge, and tips, the fuselage penalty items, and the detail part breakdown of the major surface and body components are accounted for in associated part definition routines. The structural synthesis provides the driving parameters for the part definition routines, which in turn provide the driving parameters for the cost synthesis. A detailed technical discussion of the strucutral synthesis and the part definition portions of the program is presented in Section 2. 2 of Volume II.

The cost analysis portion of the program provides: manufacturing costs based on a consideration of the actual detail parts to be produced and the actual manufacturing and assembly processes required to produce them; material costs based on the type and quantity of material actually purchased; engineering costs based on a statistical treatment of historical data; tooling costs based on the number of parts to be produced; total vehicle program costs based on a cost estimating relationship (CER) approach; and a return-on-investment analysis. Except for the total vehicle program cost and the return-on-investment analysis, input to the cost portion of the program is primarily self generated, comprised of either values that have been derived by the preceding synthesis routines or values that are generated internally as needed. A capability has been designed into the program to allow direct input of any parameters for which values are known or for which a constant value is desired. Input to the total vehicle program cost routine is comprised of a series of CER's that are typical of that particular type of analysis. A detailed discussion of the cost computations is presented in Section 2. 3 of Volume II.

3.1 VEHICLE SYNTHESIS

The purpose of the vehicle synthesis process is to provide a means for the preliminary design analyst to initially define the size and weight characteristics of a projected vehicle and its basic components. At the conceptual design stage only generalized mission and performance requirements are known, and hence available as input for the initial vehicle sizing studies. These relatively few parameters are used in the synthesis process to generate more detailed vehicle performance, weight, and geometry data. While the required input is kept at a minimum, many parameters are defined as optional input and are normally generated internally. As more detailed vehicle data is defined and fixed, the optional data may be input directly to override the internally generated data. In this way the process remains useful throughout the design definition and the fixed-configuration refinement stages of study.

An existing vehicle sizing program was expanded in scope and modified for use with interactive computer graphics. The basic routines encompassed by the vehicle synthesis process include the following: geometry, weight, performance, balance, area distribution, and cg range. The geometry subroutine derives geometry data for the fuselage, wing, horizontal and vertical stabilizers, landing gear, and engines. Basic lengths, widths, depths, areas, wetted areas, and volumes are included. The result is sufficient data to allow the construction of a general arrangement three-view drawing of the sized vehicle. Input to the geometry subroutine is made directly, and, at the user's option, may include parameters generated by the performance subroutine. Output is used to drive the weight and area distribution subroutines.

The area distribution subroutines use geometry data to generate an area ruled fuselage shape for assumed Mach 1.0 conditions. The user may view the resultant vehicle on the graphics console, and reshape the fuselage to satisfaction. The approach allows the selection of an idealized curve typical of a vehicle of the type under consideration, and the specification of maximum and minimum fuselage area constraints.

A simplified functional flow diagram of the area distribution process is presented in Figure 3-1. Output from the vehicle synthesis routines comprises a vehicle group weight statement and basic vehicle geometry sufficient to make a three-view general arrangement drawing of the vehicle. Included in the geometry output are wetted areas and volumes of major components. This data is input to the aircraft balance routine, which locates the centers of gravity for each of the elements making up the group weight statement. If the user selects an area distributed fuselage shape, the outputs from both the vehicle synthesis and balance routines are used to drive the area distribution process.

The primary steps involved in generating an area distributed body shape are as follows. Cross-sectional areas of major components are computed at specified longitudinal

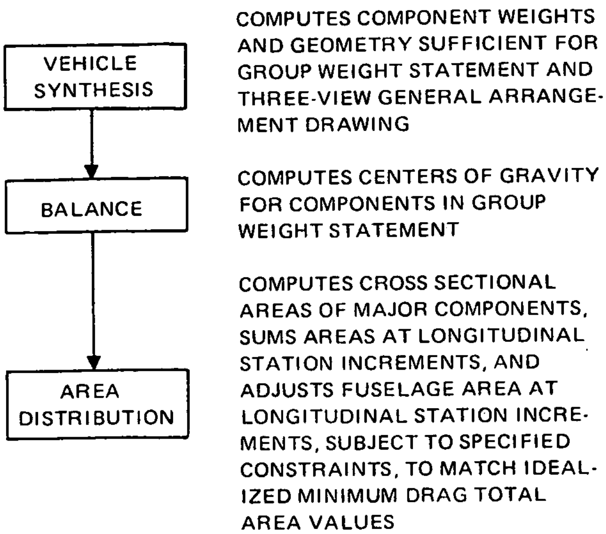

Figure 3-1. Functional Flow Diagram of Area Distribution Process

fuselage station increments. At each station a total area is derived by summing the areas of the individual components. This total area is compared to values for total area taken from an idealized, minimum drag plot of area versus station. An attempt is made to match the idealized value for total area by adjusting the area of the fuselage at each station (subject to specified minimum and maximum body area constraints), while holding the areas of the remaining components constant.

An example of a plot showing cross sectional area versus fuselage station for a typical fighter type aircraft is shown in Figure 3-2. The current version of the program computes area values for the surfaces (wing, horizontal, and vertical) and the fuselage. The remaining components (inlets, canopy, engine pods and pylons, and miscellaneous fairings) were left for future work. Figure 3-3 illustrates the actual program logic and data flow.

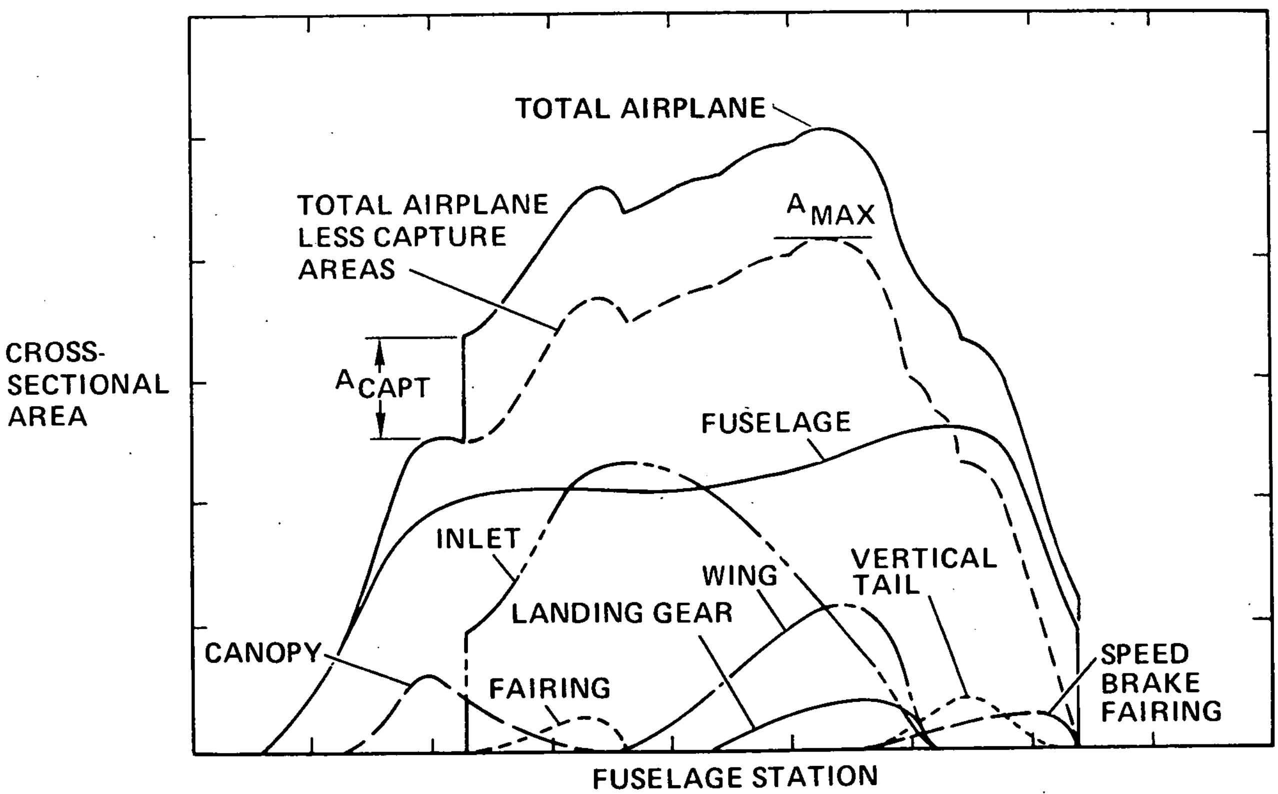

Figure 3-2. Typical Example of a Cross-Sectional Area Distribution Plot

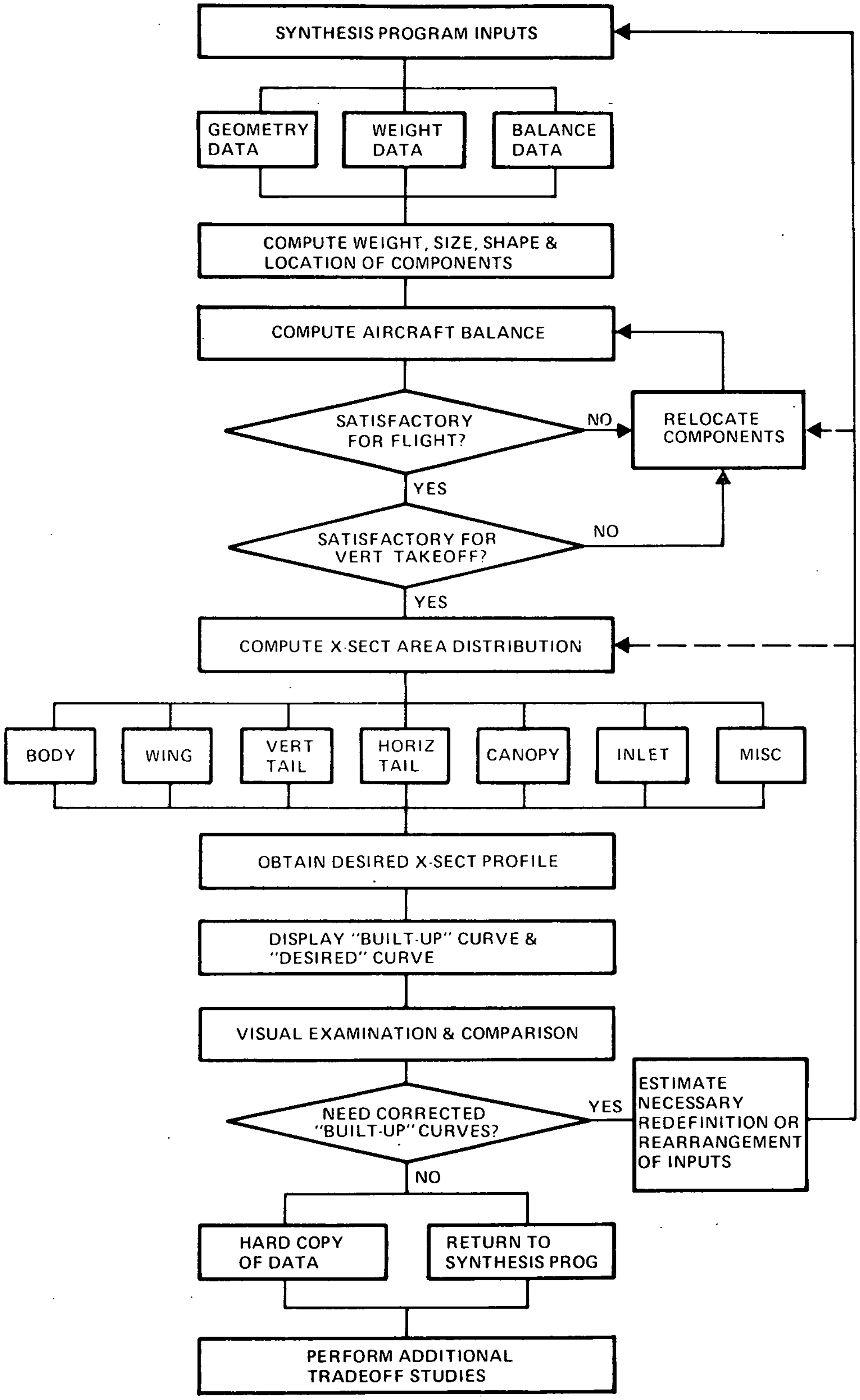

Figure 3-3. Area Distribution Logic and Data Flow

The most efficient use of the area distribution process can be made utilizing the interactive graphics mode of operation. Displays have been programmed to allow the user to view both the initial and revised area distribution plots overlayed on the idealized curve, and a plan view of the resultant area ruled aircraft. Changes that can be implemented from the console include changes to the fuselage area variation constraints, changes to the balance routine input, and changes to the vehicle synthesis inputs with a corresponding resizing of the vehicle. In this way a systematic approach to deriving the best possible fuselage shape may be accomplished, with the ability of the user to immediately examine the effects of each change.

The weight subroutine weighs the sized vehicle using statistically based weight equations. A value for initial design weight is input to establish a starting point for the sizing process. The design weight is subsequently readjusted as required to satisfy specified mission and performance requirements. The output is assembled in the format of the group weight statement defined by MIL-STD-254(ASG).

The performance subroutine provides a simplified analysis accounting for vehicle performance, propulsions, and loads. The method is intended to supply reasonable input data only in a limited number of applications, and is not designed to replace the more general analyses found in larger, more comprehensive programs. Input is comprised of parameters such as landing field length, takeoff field length, climb requirements, fuel requirements, cruise speed, range, wing loading, and aspect ratio. Output includes: lift and drag coefficients, wing area, thrust-to-weight ratios, fuel requirements, and ultimate gust load factor.

The balance subroutine utilizes the output from the weight analysis plus generalized location coefficients to compute the cg location for each aircraft item listed on the group weight statement. Vehicle cg locations are output as both a station and as a percentage of the wing mean aerodynamic chord for several aircraft weight conditions.

The cg range subroutines provide the capability to plot the cg envelope for a given vehicle "flying" a defined mission profile. Input is comprised of weight and cg data previously derived. The output allows the user to view the cg travel as various aircraft expendables are loaded onto the aircraft or are used.

The actual sizing process within the vehicle synthesis is driven by an iteration process. A test is made to see whether or not the final vehicle gross takeoff weight is within set limits (±0.1%) with respect to the initial design weight. This test ensures that the final sized vehicle computed weight is consistent with specified mission and performance requirements, and consistent with the weight values used in calculations in previous subroutines. The following logic applies:

$$\text{Test: is} \quad \frac{WT_{\text{Initial}} - WT_{\text{Calc.}}}{WT_{\text{Calc.}}} < 0.1\%$$

If yes: Display weight statement

If no: Set $WT_{Initial} = WT_{Calc.}$ and reiterate the sizing process

The initial value for $WT_{Initial}$ is supplied by the user.

3.2 STRUCTURAL SYNTHESIS/PARTS PREDICTION

The purpose of the structural synthesis is to utilize general preliminary design data of the type output by the vehicle synthesis to generate more detailed geometry, loads, and weight data for the primary structural components of the projected vehicle. The structural synthesis provides a means of descriptively designing structural components that fulfill specified requirements of strength and geometry. The structural synthesis process is comprised of two subprograms, one for the basic fuselage structural shell and one for the aerodynamic surface structural box. Both subprograms utilize a multi-station analysis to size the structural members. The balance of parts associated with the fuselage and aerodynamic surfaces are defined and analyzed in the part definition subprograms that are driven by the structural synthesis.

The aerodynamic surface structural box subprogram performs the following functions: distribution of the external loads, definition of shear, bending, and torsion, and definition of rib locations. It sizes the ribs, spars, and cover panels in terms of cross-sectional areas, thicknesses, and overall dimensions, and computes the theoretical weights. The part definition routines associated with the structural box define the surface geometry in terms of minimum gages, rib type and location, flange width, fastener size, etc. A breakdown is made of major components into detail parts, and logic parameters for process listings and the cost analysis are defined. These routines also define and size the leading edge, trailing edge, and tip geometry and weights.

The fuselage basic structural shell subprogram encompasses the following processes: distribution of the external loads, computation of the shear, bending, torsion, and margins of safety, and definition of the frame spacing and general fuselage barrel geometry. It sizes the frame and cover panel material thickness, cross-sectional areas, stiffener flange areas, lengths, etc., required to drive the detail part definition subprograms. The part definition routines associated with the fuselage shell define geometry in terms of frame stations, barrel stations, frame segment perimeters, etc. A breakdown is made of major components into detail parts, and logic parameters for process listings and the cost analysis are defined. An accounting is made for the fuselage penalty items (bulkheads, windows, floors, doors, etc.) not included in the fuselage structural synthesis subprogram.

Four types of weight data are computed within the program: 1) a vehicle system group weight statement per MIL-STD-254 (ASG), and, at the detail part level: 2) a theoretical or optimum weight (THEORETL WEIGHT), 3) an actual weight (ACTUAL WEIGHT), and

4) a material purchase weight (MTL WEIGHT). Detail part weights are summed to buildup subcomponents into subassemblies, and subassemblies into major components, etc., to derive the complete airframe assembly weight.

A group weight statement for the complete vehicle system is generated within the vehicle synthesis routines. The procedure is statistically based and utilizes a series of empirical equations derived from the analysis and extrapolation of historical aircraft weight data. This level of analysis is consistent with that normally used at the preliminary design state. The output format is taken from the weight report format specified in MIL-STD-254 (ASG).

A theoretical weight, OPWT, is generated for primary structural components within the structural synthesis routines. The theoretical weight is the weight of the basic, idealized structural element. It represents an optimum value that is based on geometry of a component sized simply for load carrying capability. Real world manufacturing and assembly constraints are not considered. Typical features not accounted for are: flanges to serve as attachment points, clearance allowances, material widths for edge distance requirements, joint load path continuity, and minimum gage.

The actual weight, ACWT, reflects the actual weight of the finished part. It is computed based on the actual geometry of the finished part, and accounts for all design, manufacturing, and assembly considerations that would normally go into producing a real part. Figure 3-4 illustrates the different concepts involved in determining the idealized or theoretical weight and the practical or actual weight. The former is based on the output from the structural synthesis routines, and the latter on the detail part definition routines.

The material purchase weight, MAWT, is the weight of raw material stock that must be purchased in order to be able to manufacture a part of actual weight, ACWT. Calculation of the material purchase weight uses the same terms as the actual weight but includes allowances for material removed during manufacturing. Operations resulting in the loss of material include the initial material cut off from the raw stock, initial cutting to size, trimming, milling, turning, drilling, etc. Figure 3-5 illustrates the difference in actual and material purchase weight for an integrally stiffened skin panel. Extruded plate is purchased. From the constant dimensions of the plate a skin panel with varied skin thickness and stiffener dimensions is machined corresponding to the varied load conditions over the surface of the skin.

The approach taken in developing the aerodynamic surface structural synthesis subprogram, BOXSIZ, was to visualize the steps followed by a preliminary design analyst in sizing the primary structural elements, and then to program each step, including the different design options which are available in each engineering discipline that drive the design process. In this way it is possible to derive an effective tool for use in optimizing the overall structure for loading, and hence for weight and cost. The

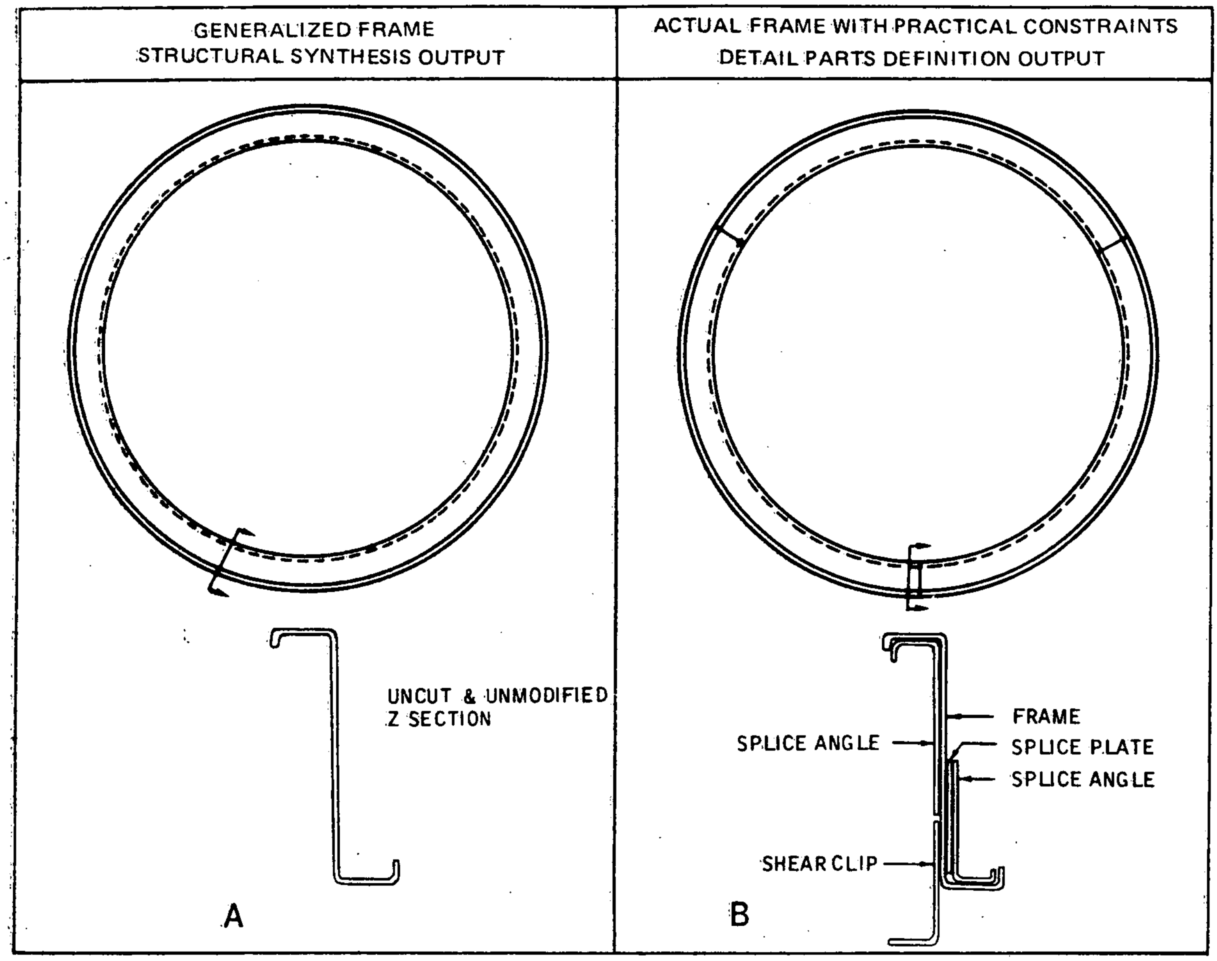

Figure 3-4. Representative Difference Between Theoretical and Actual Body Frames

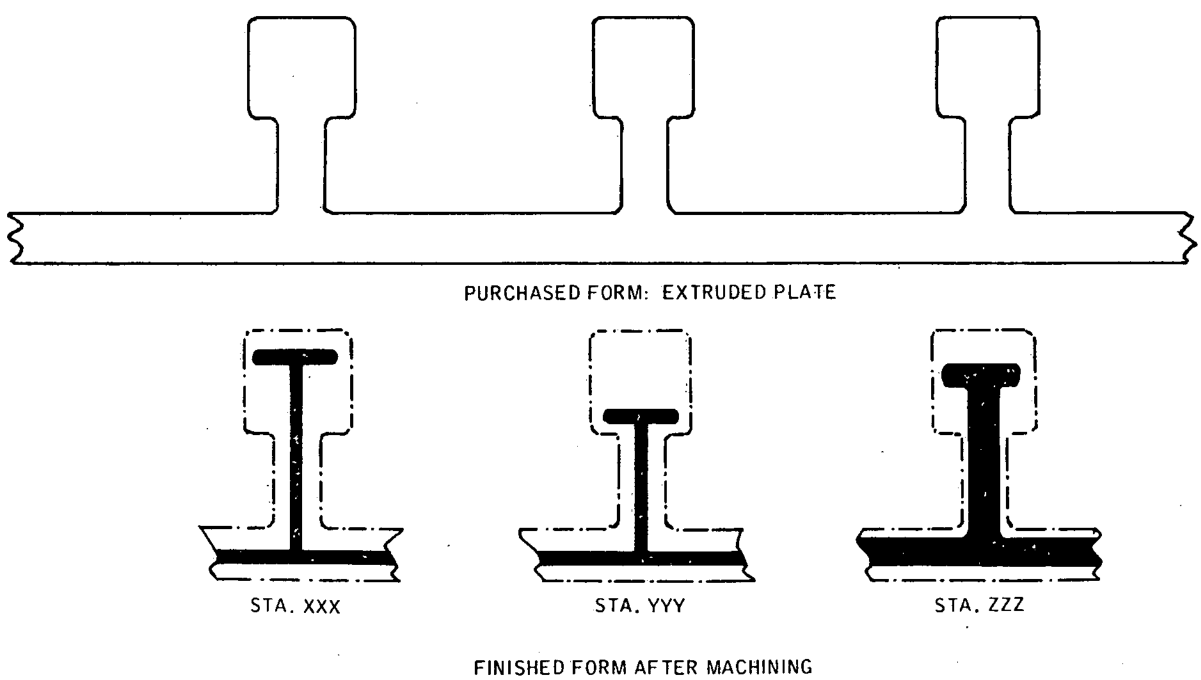

Figure 3-5. Representative Difference Between Material Purchased and Finished Form of Skin Panels

approach also allows persons with backgrounds other than each of the specific engineering design specialties to aid in generating realistic design data of an early preliminary design stage.

The BOXSIZ synthesis subprogram, comprised of 15 subroutines, utilizes a multi-station analysis and presently incorporates options for three modes of construction and eight material type selections. It should be noted that these options, while currently available in the aerodynamic surface structural synthesis subprogram, are not necessarily options available with respect to the remainder of the program. The primary components synthesized by the BOXSIZ subprogram are cover panels, spars, and ribs. A flow diagram of the routine is presented in Figure 3-6, and descriptions of the subroutines are given in Section 3.1 of Volume II.

The three modes of construction currently available are skin-stringer (multi-rib), multi-web (multi-spar), and full-depth sandwich. Generally the type of surface (wing or tail) and the mission requirements of the vehicle will guide selection of the mode of construction. For example, transport aircraft operate at high subsonic speeds and moderate load factors. The airfoil sections have moderate thickness ratios, and the skin-stringer construction usually offers the best weight efficiency. Multi-web construction is used in the wings and tails of high performance military aircraft and is associated with high speed, high load factors, and relatively thin surfaces. Ribs in this mode are usually located for a specific purpose, such as backing up an external store hardpoint or control surface hinge. Full-depth sandwich structures are most likely to be found on very thin high-speed surfaces. In cases where the selection of mode is not obvious, it is suggested that the synthesis routine for several modes be exercised and the results compared.

Skin-stringer construction, also referred to as multi-rib construction, uses closely spaced stiffening elements (ribs) and integral or attached stringers to support the skin and raise the buckling stress of the cover panel to the crippling stress of the stringer. These sections are shown in Figure 3-7. The ribs serve to distribute airload pressures and concentrated loads, and to resist crushing due to bending. Spars carry vertical shear loads and enclose the section to form a torsion-resistant box.

Multi-web construction, also referred to as multi-spar construction, is characterized by relatively thick cover panels supported by several spanwise web (or spar) elements. Cover panels are not permitted to buckle and are usually stressed to their ultimate allowables. Ribs are widely spaced and serve to introduce concentrated loads into the box. The spanwise web elements carry vertical shear and form torsional cells with the covers.

Full-depth sandwich construction uses a core of low density material to stabilize and support the cover panels and spar webs. The core is assumed to perform the function of ribs, distributing shear and crushing loads in addition to its stabilization function. Spanwise shear is carried by front and rear spar webs.

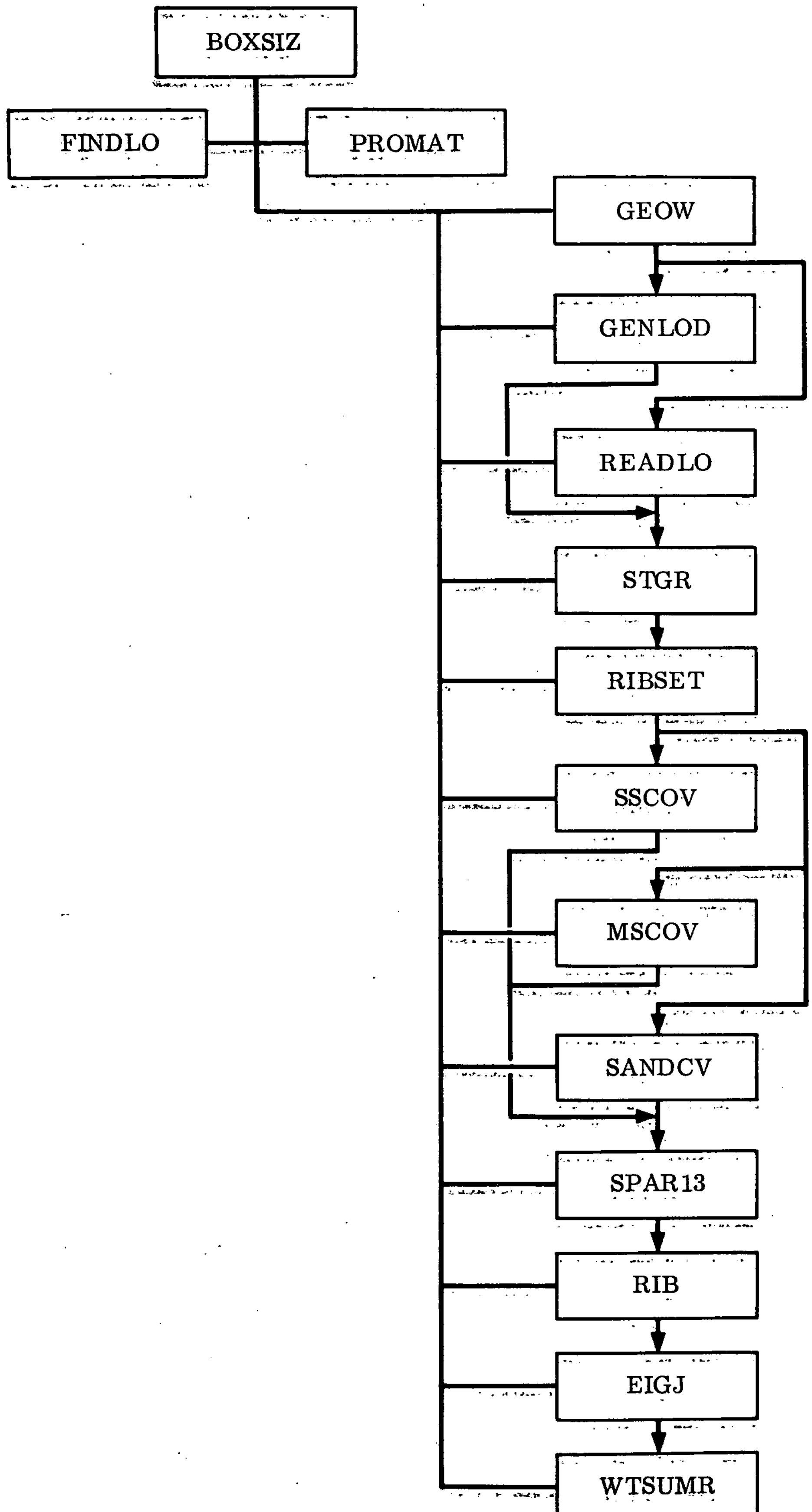

Figure 3-6. Flow Diagram of the Lifting Surface Structural Synthesis Routine BOXSIZ

Material properties, including density, elastic and shear moduli, and allowable tensile, compressive, and shear strengths are stored in the program as a function of temperature. The material type is input for the various elements along with the associated temperature environment. A separate material type and thermal environment may be specified for upper and lower cover panels, spars, and ribs. The eight materials currently available as BOXSIZ structural synthesis options are:

a. Aluminum alloy 2024-T6

b. Aluminum alloy 2024-58S1

c. Aluminum alloy 2219-T78

d. Aluminum alloy 7075-T651

e. Titanium alloy Ti-8Al-Mo-IV single annealed

f. Titanium alloy Ti-8Al-Mo-IV duplex annealed

g. René 41

h. Boron-epoxy composite

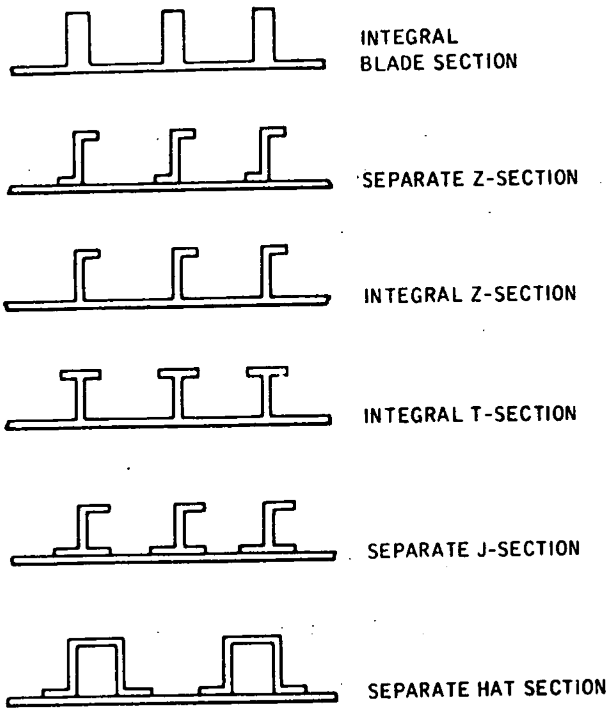

Figure 3-7. Skin Stringer Cover Panel Combinations Available in the Structural Synthesis Subprogram BOXSIZ

The spars are classified as exterior (front and rear) or interior, and basically are comprised of caps and web or truss elements. Six spar types are presently available and are shown in Figure 3-8.

The rib construction is basically the same as that of spars, comprised of caps and webs or truss elements. Figure 3-9 illustrates some examples of rib concepts.

In general the primary loading conditions result from 1) a combination of airloads due to lift and drag, and 2) inertial loads. The minimum requirement of the synthesized structure is that it support these external loads. The usual preliminary design practice is to estimate structural sizes on the basis of these loads and to subsequently refine the sizing during development stages as additional criteria and data are refined.

In order to be able to predict manufacturing costs based on the actual work to be performed, a complete list of required parts must be generated. A parts definition procedure was developed that calls out a list of detail parts when a structural component such as a wing spar or a body frame is specified by the structural synthesis routines. Each detail part is used, in turn, to call out a list of the associated manufacturing processes and the raw material stock necessary to produce that part.

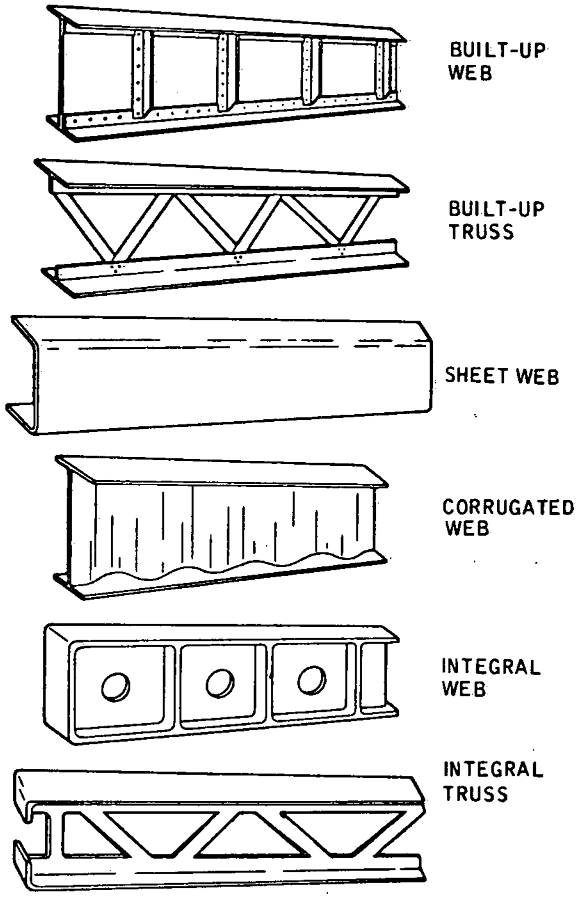

Figure 3-8. Examples of Spar Construction Types Available in the Structural Synthesis Subprogram BOXSIZ

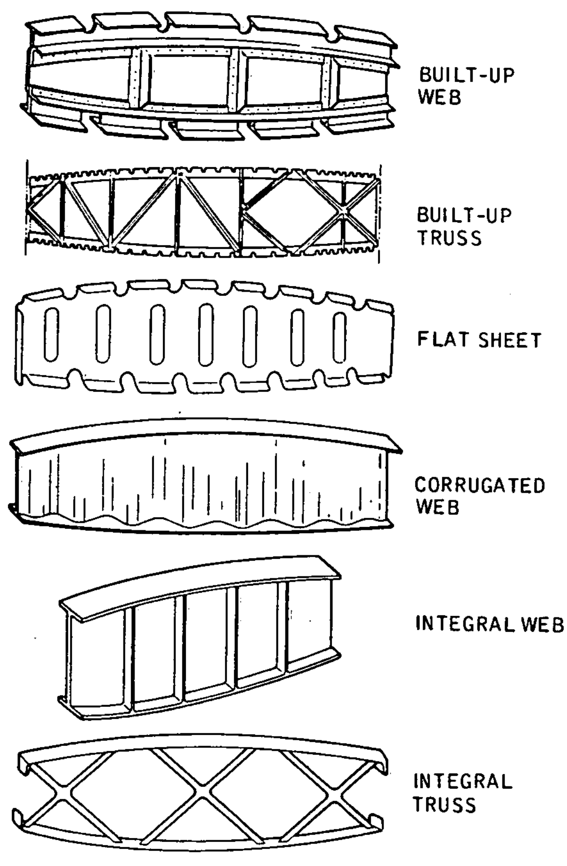

Figure 3-9. Examples of Rib Construction Types Available in the Structural Synthesis Subprogram BOXSIZ

The variables used in the parts definition routines, such as rib chord, average rib depth, number of skin panels, and fastener diameters, etc., are generated as output by the structural synthesis routines and act as input for the subsequent part definition routines. There is no direct input to the parts definition routines. Three material types are currently available in the parts definition routines: aluminum, titanium, and steel. Note that eight material choices were available in the structural synthesis routines, including the three available in the parts definition routines. The program retains the capability of adding any number of additional material and material form choices at a future date.

Table 3-1 is a summary of some of the primary structural concepts available in the parts definition procedure. Note that the selections available in the parts definition procedure do not always correspond to the selections available in the structural synthesis routines, i.e., the number of spars presently available in the parts definition routines is two, while any number of spars may be called out in the structural synthesis routines. Provision has been designed into the program for the future addition of several alternate concepts.

Table 3-1. Summary of the Available Material Forms and the Corresponding Material Form Index

Material Form Index	Material Form	Typical Part References
1	Flat plate	Spar webs
11	extruded plate	Cover panels
21	T extrusion	Spar caps
22	I extrusion	Spar rails
23	F extrusion	Rib caps, spar hinge/actuator supports, frames, longerons, intercostals
24	T extrusion	Rib and actuator stiffeners
25	L extrusion	Doubler stiffeners, miscellaneous stiffeners
26	+ extrusion	Rib braces
27	extrusion	Web stiffeners
44	Flat sheet	Shear clips, splice plates, ripstops, doublers, straps, spar doublers, clips, shims
81	Aluminum fastener	Fastener
82	Titanium fastener	Fastener
83	Steel fastener	Fastener

The leading edge, trailing edge, and tip synthesis modules provide the capability to analyze the aerodynamic surface structural components that are not considered as part of the structural box. The leading edge is defined as being forward of the front spar and includes the fixed portion of the leading edge and the leading edge high lift device (slats). The trailing edge is defined as being aft of the rear spar and includes the fixed trailing edge, foreflaps, flaps, ailerons, rudder, elevator, and spoilers. The tip is defined as that structure outboard of the structural box tip closing rib.

The synthesis includes a definition of part geometry and a detailed stress analysis that determines gages, accounts for material types, and sets minimum gage constraints. The geometry routines provide dimensional input to the stress analysis routines. The geometry and stress routines output includes part size and weight, as well as parameters for the part definition and cost routines. A generalized flow of the leading edge, trailing edge, and tip subprogram is shown in Figure 3-10.

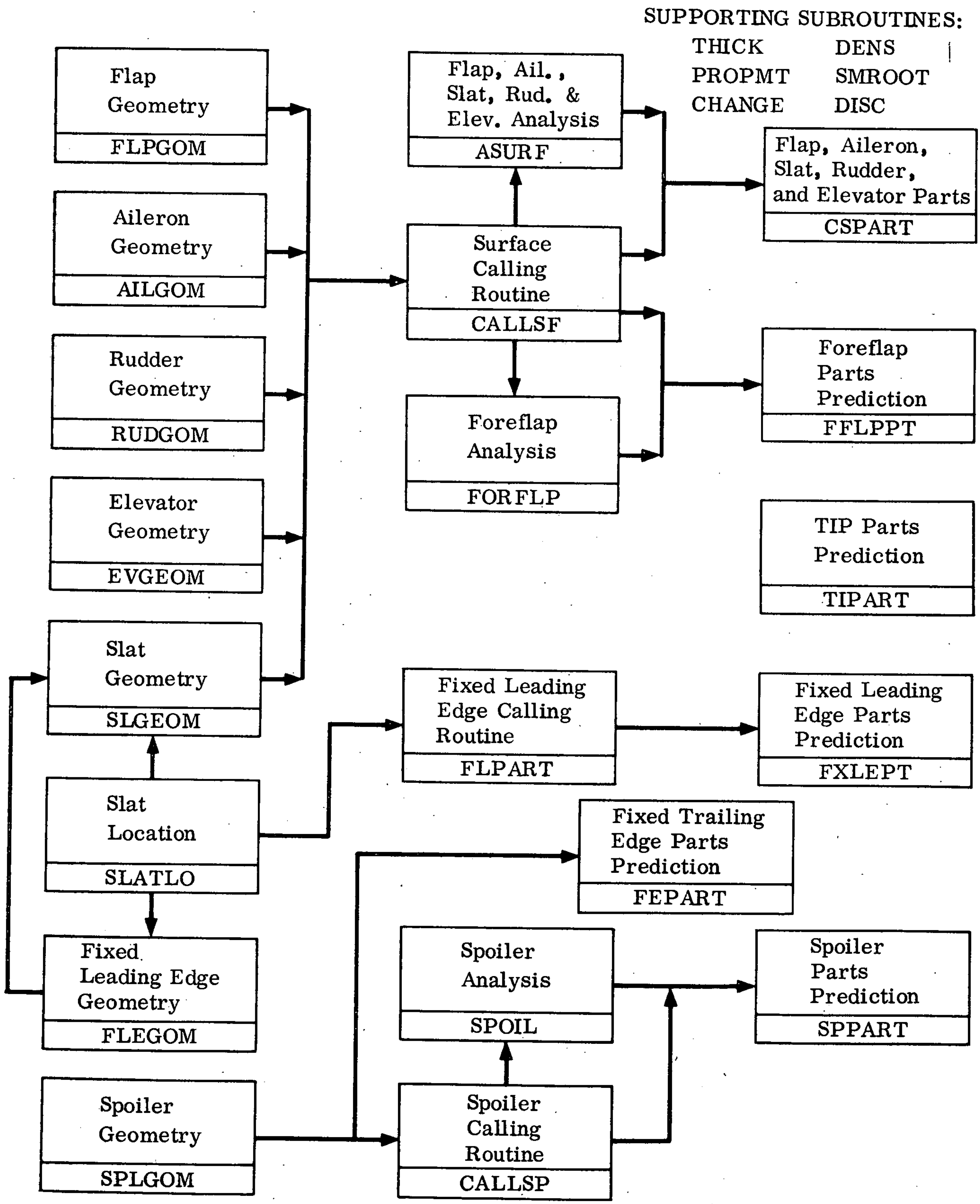

Figure 3-10. Leading Edge and Trailing Edge Synthesis Routines

The analysis utilizes nine geometry routines, three stress analysis routines, six supporting routines, and two calling rout ines. The geometry routines are for flaps, aileron, rudder, elevator, slat location, slats, fixed leading edge, and spoilers.

The stress analysis routines include foreflap, spoiler, and one which analyzes the flaps, ailerons, slats, rudder, and elevator. The supporting routines derive dimensions, material properties, and general analysis.

The tip, leading edge, and trailing edge part definition routines define the detail parts making up the fixed leading edge, fixed trailing edge, slats, flaps, foreflaps, control surfaces (spoilers, ailerons, rudder, and elevators), and tips. The data that is generated includes the number of parts, part dimensions, weight, and cost parameters. The parts definition derives its input from previous geometry and analysis subroutines.

Synthesis of the major fuselage shell components is carried out by the multi-station analysis subprogram, APAS. The approach to the synthesis process is essentially the same as that discussed earlier for the airfoil surface synthesis subprogram BOXSIZ. The fuselage shell structure is assumed to have a reasonable degree of continuity and a well-defined elastic axis. Descriptive routines provide an accurate geometry and internal loads representation. Optimization of the structural elements to provide a fully stressed design is accomplished by the use of a combination of analytical and nonlinear programming techniques. Several failure modes and physical design constraints may be recognized. Output includes internal loads data, general fuselage geometry data, and member sizes and (theoretical) weights.

The basic philosophy behind a multi-station analysis is that a set of structural elements can be derived that will satisfy given design criteria at each station. It is assumed that an aggregation of these elements will result in a reasonable representation of the structure. The primary design criterion is that the structure support the applied external loads. Other common criteria are the use of a particular material or mode of construction, and minimization of structural weight. An implicit assumption of the analysis process is that systematic revision of the elements and redistribution of the material does not significantly alter the external loads distribution.

The fuselage synthesis process requires the specification of section geometry at several control stations to account for body contour variations. Twenty control stations are permitted. Station geometry is described by locating the coordinates of nodal points on the section contour. Each cross section may contain up to 20 nodes and up to four torsional cells. Section geometry is illustrated in Figure 3-11.

A flow diagram of the fuselage structural synthesis subprogram is illustrated in Figure 3-12. The routines utilize an analysis/design refinement iterative process. One station is operated on at a time, proceeding from nose to tail. Each loading condition is processed and the full complement of structural elements at that station are satisfactorily optimized before subsequent stations are considered. The program requires

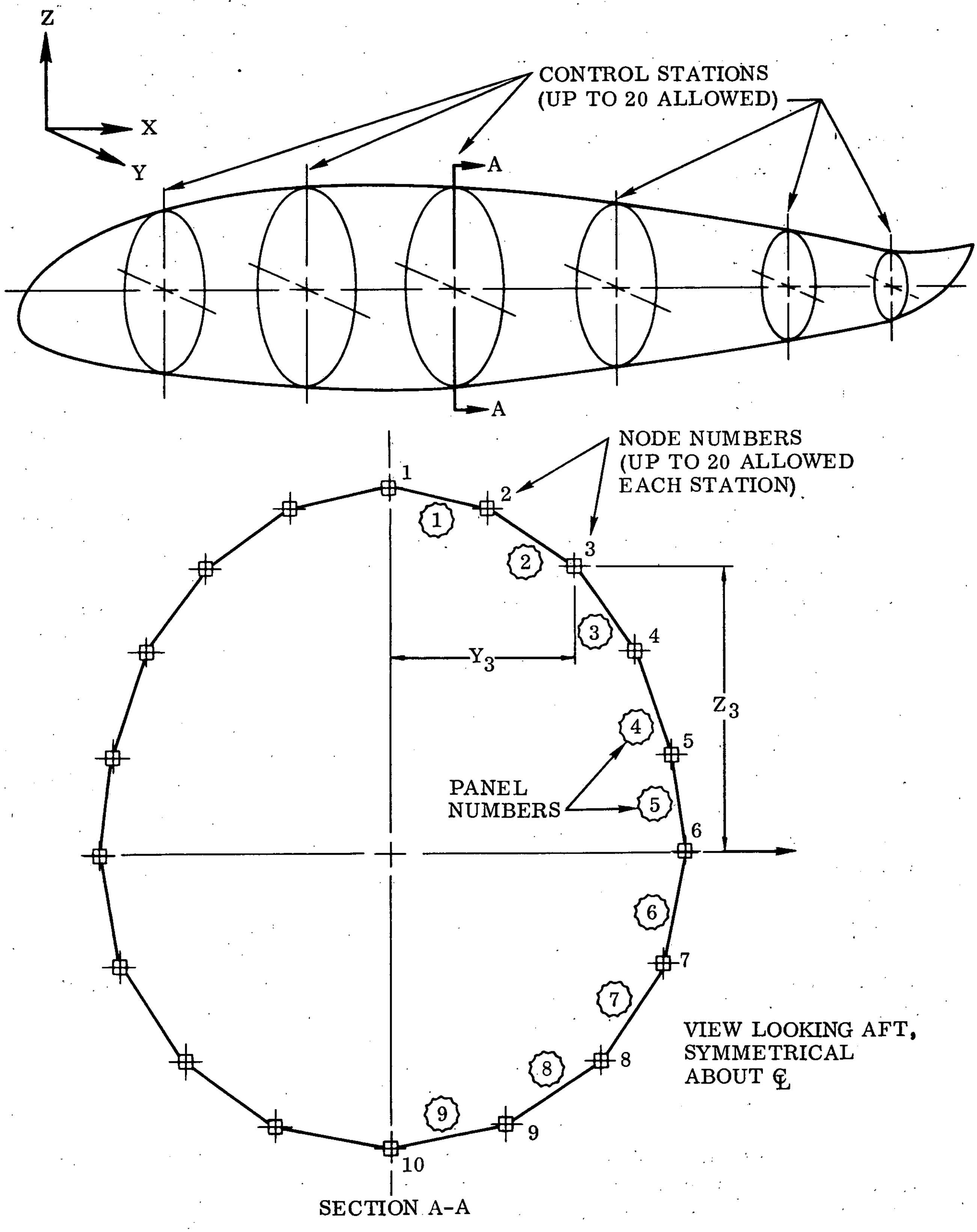

Figure 3-11. Fuselage Structural Synthesis Control Station Geometry

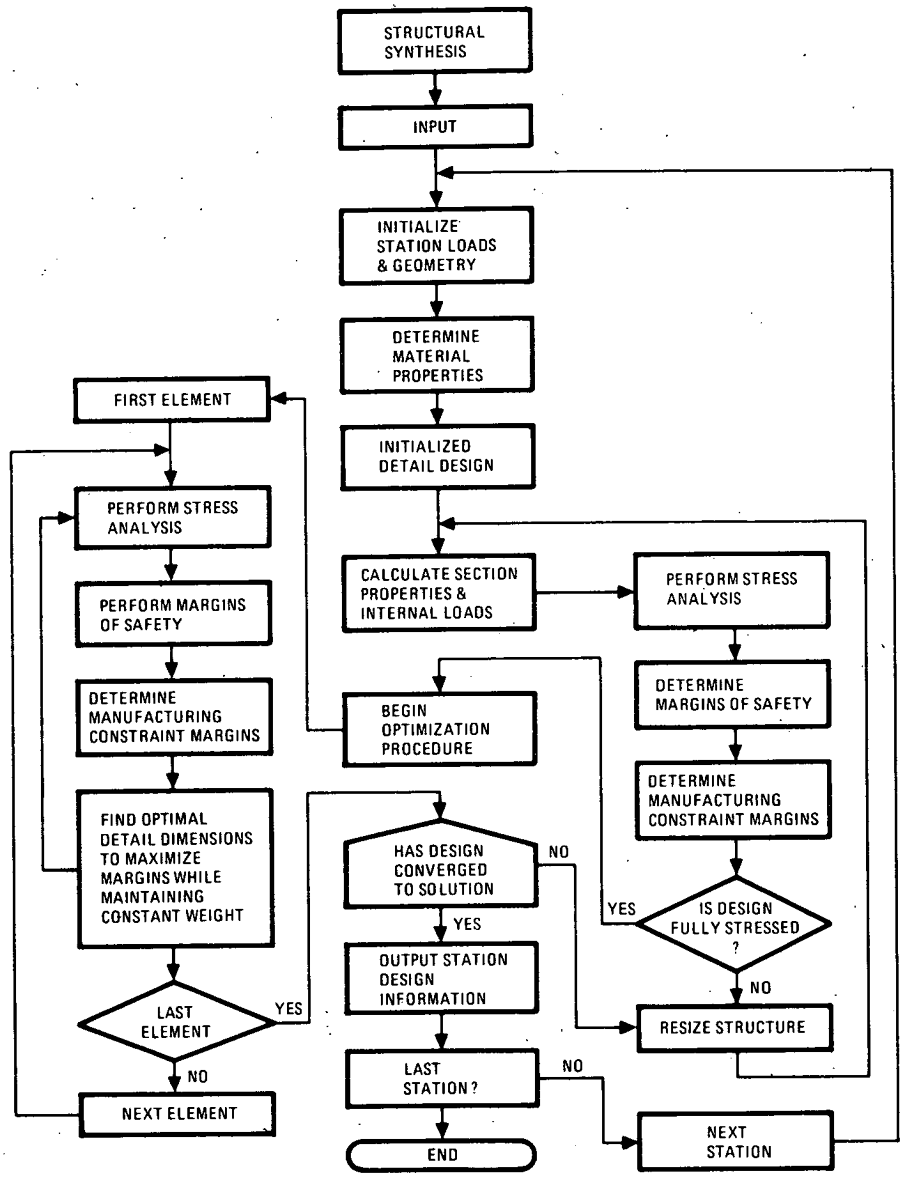

Figure 3-12. Flow Diagram for the Fuselage Structural Synthesis Subprogram APAS

an initial design point for the first analysis loop. An estimate of the cross-sectional properties may be used or the variables may be set to unity. Each dimensional variable may also have a range specified by maximum and minimum values. The limits on this range subsequently become constraints during the optimization process. These constraints are a practical way of specifying minimum gage or constancy of other features such as stringer pitch. Fully effective material is used to compute section properties.

The structural synthesis routines produce general fuselage geometry at each control station. Data generated for each station includes barrel perimeter, frame spacing, panel cross section dimensions, panel stiffener spacing, etc. The parts definition routines take the output from the fuselage structural synthesis and derive the detail parts sufficient to construct the complete basic fuselage shell structure.

The actual parts definition process is comprised of four steps. First, the complete skin panel assembly is derived: the corresponding parts are skin, stringers, and ripstops. Second, the complete frame assembly is derived, comprised of frame segments, frame splice angles, shear clips, and shear clip splice plates. Third, the parts necessary to assemble each fuselage barrel section are derived, including internal and external longitudinal skin panel splices, intercostals, and intercostal clips. And fourth, the parts required to assemble the barrel sections into a complete fuselage shell are derived: stringer splices, barrel finger splices, barrel strap splices, and splice plates. For each detail part originated a theoretical weight (OPWT), an actual weight (ACWT), and a raw material purchase weight (MAWT) is computed. Fasteners are accounted for as each group of parts is brought together to form an assembly.

The treatment of fuselage penalty items encompasses windows, doors (landing gear and side loading), and floors. The analysis is comprised of a statistically based actual weight computation and a unitized manufacturing cost computation. The values derived for fuselage penalty weights and costs are added to those of the basic fuselage shell (which are determined from a structural synthesis/parts definition analysis) to obtain total fuselage data.

3.3 COST SYNTHESIS

The cost analysis portion of the program incompasses the following: manufacturing cost, material cost, engineering cost, tooling cost, total vehicle program cost, and return-on-investment. Manufacturing cost is determined as a function of the actual shop processes necessary to produce each part. From this the corresponding number of labor hours that are required can be computed, and hence, the manufacturing cost.

Material cost is derived on the basis of the amount of raw material stock purchased, material type and form, and various extra cost items such as special lengths, widths, and tolerances.

Engineering cost is derived on the basis of equations originally developed by Levenson and Barro. Both initial and sustaining engineering costs are represented.

Tooling cost is derived on the basis of the number of dissimilar parts to be produced, and hence, the total number of tools required. Basic tooling, rate tooling, and sustaining tooling costs are represented.

Total vehicle program costs are derived using primarily the cost estimating relationships developed by Kenyon. A learning curve approach is applied to adjust first unit costs to those of subsequent units.

A return-on-investment analysis utilizes computed aircraft performance parameters and the 1967 Air Transport Association formula to derive direct operating costs. Indirect operating costs and return-on-investment are derived on the basis of an input traffic route structure. All cost data are computed relative to a specified dollar reference year. Actual cost estimation methodology is discussed in detail in Volume II.

The technique being used to estimate first unit manufacturing costs basically is as follows. A breakdown of major vehicle components into their detail parts is accomplished through the use of vehicle synthesis, structural synthesis, and part definition operations. The actual manufacturing cost analysis is based on calculating the material, and direct and indirect labor costs associated with the fabrication and assembly of each detail part. For each part, in turn, a record of manufacturing and assembly operations required to produce that part and integrate it into the vehicle structure is established. For each operation specified the number of direct or actual labor hours required to perform the operation is derived, and based on this, direct labor and indirect overhead costs are calculated. From the part geometry, the material required for each part is derived, and based on this, material costs are calculated. Figure 3-13 summarizes the steps necessary in determining the manufacturing cost from the detail part level.

The part definition routines were designed to provide an accounting of the detail parts required to produce a complete airframe. Each detail part is looked at individually and analyzed in terms of the manufacturing and assembly processes associated with it. In order for this analysis to be performed it was necessary to be able to internally account for each of the required shop processes.

To develop the process lists associated with each part, a library of shop planning records was established from existing production articles. These documents were studied and used to identify the typical processes associated with each part. A method was developed to internally relate each part to its corresponding list of processes. It was the intent to provide a means of internally generating the equivalent of a shop planning order. A representative example of such an order is presented in Figure 3-14. It is from this type of document that the specific planning for the production of an individual part can be implemented.

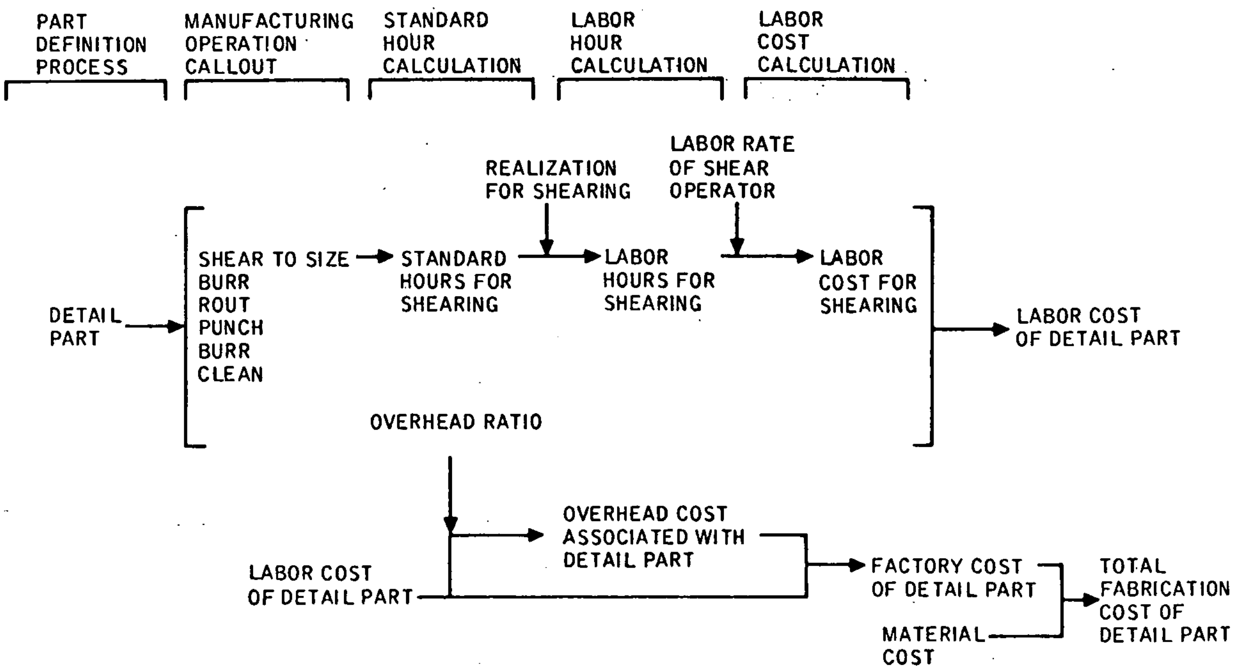

Figure 3-13. Cost Analysis Sequence Based at the Detail Part Level

Standard hours are, as the name implies, a standard time, measured in hours, which represents an optimum for the time required to perform a given task. They are the number of hours it would take for a normal person to do a normal job under normal conditions. They do not include allowances for fatigue, personal needs, rest breaks, machine adjustments or tool breakage, close tolerance work, etc. Thus, the standard hours are an idealized time scale against which actual time may be compared.

Standard hours are used industry-wide for estimating purpose. They are established by industrial engineering departments through the analysis of time and motion studies carried out for standard shop operations and procedures. They are used by industrial engineering departments to estimate the time required to perform production tasks, and by accounting departments to measure performance through comparison with actual times. By being able to estimate an optimum time in standard hours and the measuring a corresponding real or actual time, relative efficiency factors (or realization factors) can be established for various shop processes and tasks.

Included as a part of the shop planning order (Figure ~~2-36~~ 3-14) is an estimate for the number of standard hours corresponding to each shop operation. The program, following a parallel logic, was designed with a capability to generate a number of standard hours corresponding to each of the internally generated shop processes. This is accomplished by a series of standard hour equations derived based on standards data acquired through the industrial engineering department.

GENERAL DYNAMICS CONVAIR	M-DAY LTR-NO PRJ PART NUMBER
SHOP ORDER PLANNING	363 D 8 4T11001-125A

PLANNER	GRP	CHG CD	ENGRG D/C	P/L	INSP CL	NO	LTR-NO	PRJ	PART NUMBER
EBROLASKI	11	RC	OD			26	D	8	4T11001-125A

TITLE	MATERIAL PERCENT	GRP	NUMBER	A/Z
STIFFENER	3.000	12	120239	D

MATL DESCRIPTION	GAU/DIA	WID/WALL	LENGTH	SPECIFICATION	COND	PTS	OP/END	PT-CL
SEE NOTE A			30.000	QQ-A-200/11	NOTE	01		2

DATE	STK RM	QTY	BY	SPARE	CUST	SHOP	INSP

-----OPERATIONS-----

INSP STMP	DEPT	CC	OPER NO	OP SCH	OPERATION DESCRIPTION TOOL/SPEC NO	TOOL SEQ NO	TOOL SYMB	MACH CODE	SET-UP TIME	RUN TIME
			A		LS39048-1 7075T6511 EXTRU					
			B		STP63-001 STP58-208 STP57-301 STP53-201 DS30004 STP59-201					
	836	07	10		SAW TO LENGTH 1-1 4T11001-125A		SP	6880	0.12	0.0031
			15		INSPECT					
	01	03	20		ROUT 4T11001-125A 4T11001-125A		MAST SP	6455	0.08	0.0256
	01	02	30		DRILL PILOT HOLES (74) PLCS 4T11001-125A		DLT	1552	0.25	0.1750
	01	12	40		BURR			2905		0.0155
	01	12	50		IDENTIFY (TAG) STP63-001 4T11001-125A		SP	2910	0.07	0.0008
			55		RW					
			65		INSPECT					
	02	05	70		ALK ETCH STP57-301			5845		0.0216
	02	11	80		SULF ANODIZE STP58-208			5807		0.0144
			85		INSPECT					
	02	03	90		(1) ZCP STP59-201			4815	0.10	0.0052
	02	03	100		IDENT R/S STP63-001 4T11001-125A		SP	2910	0.07	0.0032
			105		INSPECT					
			115		HPS1-00156 (PROTECT)					
						TOTAL			0.69	0.2644

Figure 3-14. Example of a Shop Planning Order for a Rib Brace

Standard hours are computed as an intermediate step in the process of deriving actual labor hours. The conversion is accomplished by making use of the realization factor, a measured value representing shop efficiency as discussed below. The equations for actual labor hours take the following form:

Actual Labor Hours = Standard Hours/Realization

Labor and overhead rates are used in the program to calculate labor and overhead costs, based on the number of actual labor hours required for each manufacturing and assembly process. Labor rates reflect the wages paid directly to the individual employees for each hour of clock time. The rates do not include fringe benefits or company contributions to retirement, social security, state unemployment, etc., which are considered part of the overhead cost. Also included as part of overhead are indirect labor costs, maintenance, supplies, taxes, insurance, depreciation, etc. Labor rates are largely uncontrollable by management, being a function instead of union/management agreements and reflecting current labor supply and demand, general economic conditions, and inflation. Labor rates are a function of time and are readily predictable for the near future.

The overhead ratio is the ratio of overhead costs to direct labor costs. It is established based on historical accounting records, and is, in turn, often used by estimating departments. In the program, the overhead ratio is used to determine the overhead costs corresponding to the calculated labor costs where:

Overhead Cost = Labor Cost * Overhead Ratio

Realization is a measure of shop efficiency, and as such, it varies from department to department and from day to day within a department. Realization data for the various departments involved in production tasks at the San Diego operation has been collected, studied, and adapted for use with the program. Realizations can be specified either as a constant average value or as a time dependent equation. Some of the factors affecting realization are:

a. Worker personal needs.

b. Rest periods.

c. Inaccurate planning of the task.

d. Change in procedure, machines, or tools without corresponding change in manhour estimates.

e. Machine breakdown.

f. Tool breakage and part spoilage.

g. Availability of previous setups.

h. Use of special supervision.

i. Ability and effort level of individuals assigned the task.

Labor and overhead costs are computed directly for the first unit. A learning curve approach is applied to first unit costs to derive the cost of any subsequent unit or production lot. Labor (and overhead) costs are generated at the detail part level. For each manufacturing or assembly process specified for a given part, a value for standard hours, actual labor hours, labor cost, and overhead cost is computed. These are summed to obtain total costs for a given part, subassembly, assembly, etc.

Material costs are computed based on the material type (aluminum, steel, etc.), material form (sheet, plate, bar, etc.), and the raw material purchase weight. The actual calculation of material cost takes the form:

$$MATCOS = AMUV * COSWT * MAWT$$

where

MATCOS is the material cost

AMUV is the manufacturing usage variance factor explained below

COSWT is the material unit cost

MAWT is the raw material purchase weight

The computation of material costs requires the derivation of a material unit cost (COSWT) and the definition of a manufacturing usage variance factor (AMUV). The computation of the material purchase weight (MAWT) is done during the weight analysis portion of the program.

The material unit cost is, in general, a function of the material type, form, quantity of material bought, and special feature requirements such as special lengths, widths, thicknesses, alloys, tempers, tolerances, and marking. Computation of the material unit cost can be summarized as follows: a base price is computed as a function of material type and form; the base price is adjusted to account for the quantity buy price differential; the prices of appropriate special feature extra cost items are computed and summed to derive a total special feature penalty cost; a total material unit cost is determined by summing the adjusted base price and the special feature penalty cost; and finally, the resultant value for material unit cost is adjusted, if necessary, to correspond to dollars for the specified reference year.

The manufacturing usage variance factor AMUV is the ratio of the actual amount of material purchased to the original estimated amount of material required for manufacturing. The factor is, in general, a function of material type (particularly in the case of advanced composites) and past material handling experience. The factor results from material and part overbuying to account for normal indirect material losses

during the manufacturing phase of production. These losses include material and part spoilage, duplication, substitution, changes, waste, etc. These losses are to be differentiated from those resulting directly from manufacturing, such as trimming, routing, and milling, which are accounted for in the derivation of the material purchase weight.

The actual value for the manufacturing usage variance factor is determined by accounting procedures. A nominal value of 1.10 is currently in use by the program for all material forms. This represents a 10% overbuy, and is a fairly good average value for typical metallic aircraft construction. However, it is somewhat high for production involving the use of advanced composite materials.

Engineering costs are computed by deriving the number of engineering manhours required and multiplying this by a composite engineering labor rate. Engineering hours are computed as initial engineering hours – those hours which are utilized by the time the first airframe has been completed – and sustaining engineering hours – those hours occurring after the first airframe has been completed.

The actual computation of initial and sustaining engineering hours has as its basis equations developed by Levinson and Barro. For this reason their definition of the engineering task was used. Engineering, then, was defined as including the following: design and integration studies, engineering for wind tunnel models, mockup and engine testing, test engineering, laboratory work on subsystems and static test items, development testing, board hours, release and maintenance of drawings, specifications, shop and vendor liaison, analysis and incorporation of changes, material and process specifications, and reliability. Hours not considered as engineering include those associated with flight test, planning, ground handling equipment, spares, mobile training units, and publications. Also not included as part of engineering cost are travel and computer time.

Engineering labor rate may be input directly as a user option. If a value is not input a rate is computed based on the reference year. A single rate is applied to all engineering tasks.

Tooling costs are comprised of three primary elements. They are: basic tooling which is the first level of tooling designed to support the initial production lot at the initial production rate, rate tooling which is the second level of tooling established to support the remainder of the production schedule at the maximum production rate, and sustaining tooling which is the tooling effort required to support the entire production schedule by providing for tool maintenance and producibility charges.

Each of the three tooling elements can, in turn, be broken down into manufacturing, engineering, and materials. Tool manufacturing includes the following: tooling machine shop, template shop, plastic pattern shop, foundary, jigs and fixtures, tool and die, form blocks, and plastics. Tool engineering includes tool design, tool and

operations planning, tool project engineering, numerical control programming, tool liaison, production control, and proofing. Tooling materials include materials and graphic reproduction support.

Tool engineering and manufacturing labor rates may be input as a user option. If a value for either is not input, a rate is calculated based on the reference year.

Total vehicle program costs are computed based on a cost model which was assembled primarily utilizing the work of Kenyon. The model incorporates a general format similar to that used by Kenyon although equations taken from the literature have been substituted in several places. Where possible values for various cost elements that have been computed elsewhere in the program are brought across. These include first unit manufacturing costs (wing, body, horizontal, vertical, and nacelle), initial and sustaining engineering costs, basic tooling costs (basic tool engineering, manufacturing, and material) and rate and sustaining tooling costs.

The direct operating cost computation requires as input the aircraft price, as previously computed in the total vehicle cost module, and aircraft performance, defined principally as fuel and time required for various distance increments up to the operational range. The input when applied to the 1967 Air Transport Association formula develops direct operating cost elements for specified distance increments. The Air Transport Association formula provides the basis to compute crew cost (primarily a function of the number in the cockpit crew), time to cover specified distances, and aircraft gross weight. Fuel and oil costs are computed directly from block fuel required. Insurance (hull insurance only, liability is an indirect cost) is computed as an annual percentage of the aircraft price. Maintenance is computed as a function of time, weight, thrust, and hardware cost. Depreciation is computed for a specified number of years, and includes depreciation of spares as well as primary flight equipment. The resultant output is direct operating cost per aircraft mile and per available seat block for various distances up to the operational range of the airplane.

To compute return-on-investment data, a comparison is made between revenue and direct plus indirect operating costs. City pair traffic data, distances, and fare formula establish the revenue of interest. Aircraft capacity, frequency, and load factor constraints determine the required flight frequency, indirect costs, and fleet size. Indirect costs are generally computed in accordance with the Lockheed formula by city pair for such factors as aircraft servicing, stewardess expense, food, reservations and sales, baggage handling, and general and administrative expenses.

To compute return-on-investment, total income minus total cost is compared to total investment as determined by fleet size, aircraft price, and spares factors. Return-on-investment is calculated as that percentage return on net invested capital (initial investment minus cash flow from depreciation) that would equal the same percentage return on fixed return investment, such as an accrual savings deposit. Return-on-investment is computed for each city pair and for the entire system. In this way, it

is possible to establish the traffic and distance requirements to make a given aircraft profitable and to make a meaningful comparison between two airplanes where seating capacity, performance, and price are different.

SECTION 4

STUDY RESULTS

4.1 PROGRAM DESCRIPTION

The results of this study were programmed for a CDC 6000 series digital computer and a CDC 250 processor/CDC 252 CRT display console. A block diagram illustrating the program and the flow of information between subroutines is presented in Figure 4-1. Input is read utilizing the NAMELIST library subroutine. A total of 15 separate functional blocks of data are required. Output is comprised of the following:

Group Weight Statement Geometry Data Performance Data Balance Data	Vehicle Synthesis
Loads Data Geometry Data Theoretical Weight Data	Structural Synthesis
Theoretical Weight Data Actual Weight Data Material Purchase Weight Data Parts Listing	Parts Definition
Manufacturing Costs Material Costs Engineering Costs Tooling Costs Total Vehicle Program Costs Return-on-Investment	Cost Analysis

In formulating the logic processes and communication links used by the program, several ground rules were followed. It was the intention to make the program as flexible as possible from the user's (application) standpoint and also from the programmer's (modification, update) standpoint. The actual program deck is comprised of nearly 200 functionally independent subroutines. This high degree of modularity provides a means of program updating or modification simply by removing a complete subroutine and replacing it with a new version. The new subroutine, which is restricted only to retaining the same input/output communication links, may deffer by only a card or two, or may pursue a whole new analysis procedure.

A special feature of the program is its ability to generate much of its own required data. This is a result of the coupling of several levels of synthesis routines, each acting as

the driver for the one that follows. The output from the vehicle synthesis is used as input by the structural synthesis routines, whose output in turn is used as input by the parts definition routines. This procedure results in input requirements that are, for the most part, on a very generalized, descriptive level consistent with typical preliminary design data. Included as part of this capability is the concept of optional input. The optional portion of the input is comprised of a series of parameters that are not always known during initial vehicle studies. Capability is built into the program to automatically calculate typical values for these parameters if they are not input, but if they are available and input, the internal calculation is suppressed and the input value is utilized.

It was found that because of the degree of detail considered, the cumulative volume of output data available often became burdensome. A capability to suppress portions of the output was built into the program. This allows the user to tailor the output to the job at hand. Any combination of output may be selected, from a complete and fully detailed version, to a version consisting of a series of summary sheets.

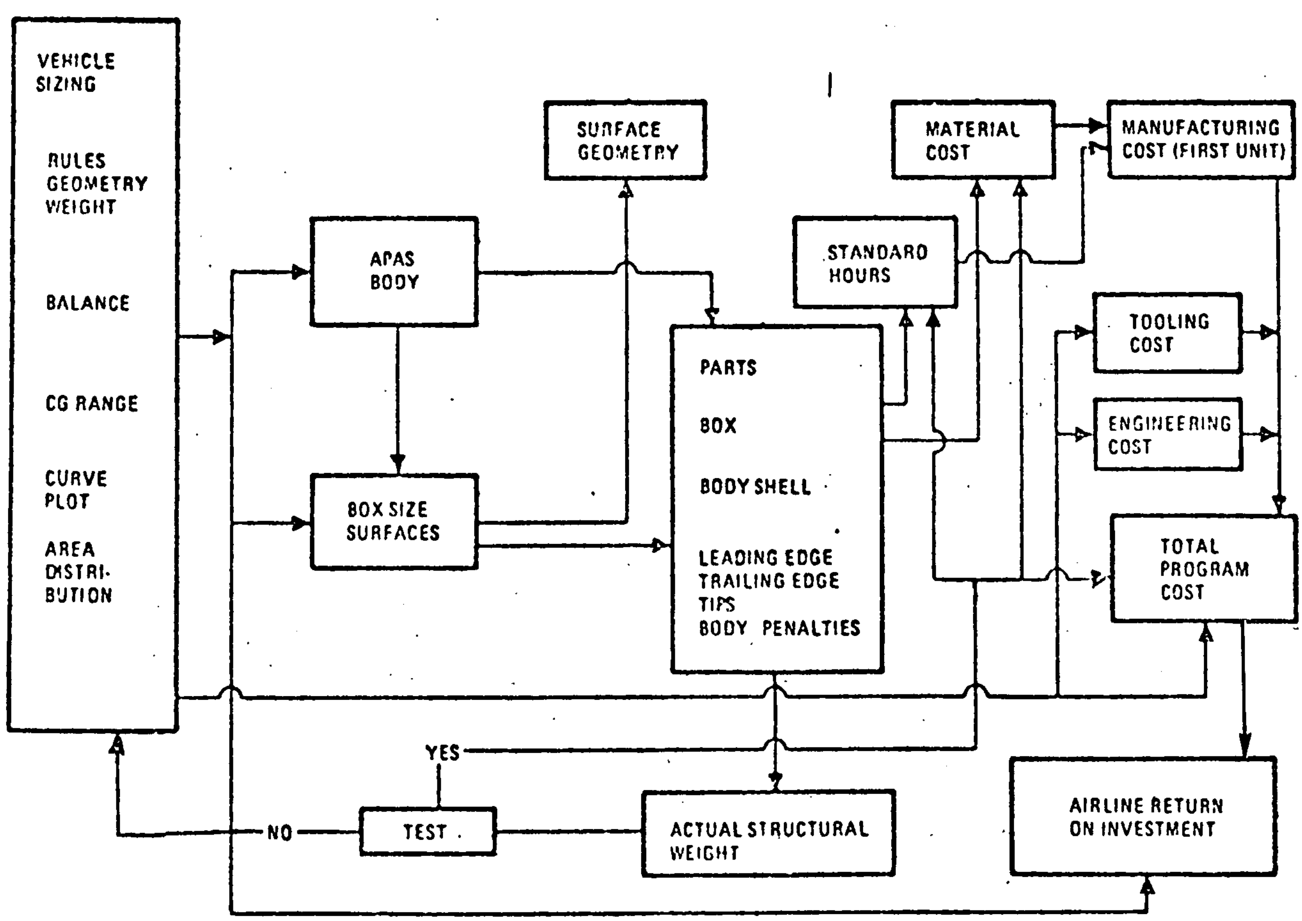

Figure 4-1. Information Flow Between Functional Blocks

4.2 APPLICATIONS

The program is intended for use at the preliminary design level, and requires a minimum amount of input data. However, the actual depth of analysis reflected internally by the program allows its use to be extended to a degree into the detail design stage. To accomplish this purpose the program was designed to accept much of its input data on an optional basis. The so-called optional input is comprised of parameters that are not always available at the preliminary design stage, but that are often defined at a slightly later stage. These variables may be input by the user if they are known; or, in the absence of a direct input, values are computed internally by the program.

It is intended that the program be applied to the investigation of weight and cost sensitivities of airframe structures to various design alternatives. The advantage provided by the program is its ability to make cost and weight tradeoff studies at several levels of consideration. For example, weight and cost data can be related directly to key system parameters at the vehicle mission level such as payload, speed, range, and landing field requirements. At the vehicle configuration level, data can be related directly to surface areas, span, sweep, taper, etc., and fuselage length, slenderness, etc. At the major component level comparisons can be made between different materials, modes of construction, detail part makeup, etc. The program provides a means of refining aircraft design in terms of cost and weight to a high degree of detail.

The current version of the program is directed mainly at subsonic transport aircraft. Some factors limit consideration of other aircraft types. The RULES subroutine in the vehicle synthesis process derives a wing loading from the landing field length requirements. This is a typical design feature for transports but not necessarily one for high performance aircraft. This limitation may be circumvented by inputting directly a value for wing loading (or wing area) and fuel weight. In this case the RULES subroutine is bypassed.

The assumed structural arrangements and parts lists are those of a typical transport. Data from the DC-10 fuselage, 880 wing, C-141 empennage, and C-5 empennage were used to establish the data base for the program. There is no reason a variety of aircraft types could not be analyzed using the program if the parts lists and associated analyses were extended.

The program was designed to be run both in a batch mode or in an interactive graphics mode of operation. For the latter case, control of the program is transferred directly to the user. From the graphics console the user may study the output from various portions of the program, make changes to the input and recompute, plot the effects of changes in various vehicle parameters, check overall vehicle balance and plot the center of gravity envelope for a specified mission, tailor an area ruled fuselage shape, and inspect a three-view representation of the sized vehicle. The advantage of the interactive graphics interface is that the program user can work with the computer

in real time, combining the rapid response and data handling capabilities of the computer with human judgement and direction. In this way the user can direct the design analysis process step by step, immediately seeing the effect of any changes made.

It was anticipated that a program of this type would be updated and refined on a fairly continuous basis. For this reason the program incorporates a highly modularized format. Each subroutine was made to be as independent as possible of the rest of the program. Changes can be made to a single card or two, or an entire subroutine can be "unplugged" and replaced with a new one. The only requirement for the new subroutine is that the input/output interface be preserved for communication and data flow. Hence, it is possible to always have a usable version of the program available, even though new subroutines are in the process of being developed and checked out independently.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the conclusions reached as a result of this development effort. Recommendations are made for future extensions and refinements of the methodology developed. In general, the analysis reflected by the existing program is adequate, but it was found that an increased depth of analysis in several areas would provide a payoff in increased accuracy or sensitivity.

a. A weight and cost estimating methodology for aircraft applications at the preliminary design level was successfully developed. The results of the study effort have been favorably correlated with aircraft data in several test cases. The program provides a highly flexible and sensitive means of deriving detailed weight and cost information with a level of input consistent with the preliminary design level.

b. The output of the vehicle synthesis routine was shown to be sufficient to act as a driver for the structural synthesis routines. Because the vehicle synthesis routine is already in common use at the preliminary design level, its input requirements reflect a level of information readily available at this stage. The interactive graphics interface was shown to provide a valuable tool for making rapid trade studies between large numbers of alternative vehicle configurations. A simplified performance analysis is provided, which, at the users option, may be utilized to generate part of the input required by the vehicle synthesis routines. Performance parameters for which an internal computation is available include lift and drag coefficients, wing loading, thrust to weight ratios, fuel requirements, and gust load factors.

   It is recommended that as a future refinement to the program, a more comprehensive performance analysis be coupled with the vehicle synthesis routines. An improved capability for modeling the projected aircraft mission would provide an added degree of flexibility in the determination of basic aerodynamic, propulsion, and load parameters, and an overall improvement in the accuracy and utility of the initial sizing process.

c. An area distribution routine was developed which successfully generates an area ruled fuselage shape subject to user-specified constraints. Displays were programmed to allow the user, working from the interactive graphics console, to view the area distribution plots and the planform of the resultant aircraft, and to implement changes to the input or constraints.

d. The capability to directly generate an accounting of aircraft balance utilizing the output of the vehicle synthesis routines was achieved. A center of gravity for each item listed on the group weight statement is derived along with the overall aircraft center of gravity for several weight conditions. A visual study of center of gravity travel for various mission weight conditions may be made by utilizing the center of gravity range plotting routine.

e. A generalized curve plotting capability was incorporated into the program. The user, working from the graphics console, has the ability to generate and display families of comparison plots for any two parameters from the vehicle synthesis routines.

f. The structural synthesis routines were shown to be effective as intermediate steps in the parts list breakdown procedure. The output from the vehicle synthesis proved to be sufficiently detailed to provide a large amount of the required input to the structural synthesis routines. The resulting data from the structural synthesis proved to be adequate for developing the parts listing or parts definition procedures.

   It is recommended that the BOXSIZ lifting surfaces portion of the structural synthesis be replaced with the lifting surface routines of APAS. This would add a degree of programming consistency (the body structural synthesis is from the APAS program), and would provide the most up-to-date analysis available that is suitable for preliminary sizing.

g. It was shown to be possible to develop a system of functional logic for the prediction of detail part lists based on the output of the structural synthesis routines. The end result of the parts definition process was a complete breakdown of the airframe structure into its component detail parts. This parts list represents the basis of the actual weight and manufacturing cost analysis. A sequence of assembling the detail parts was established. This assembly sequence represents the basis of the assembly cost analysis.

   It is recommended that the current parts list be updated and refined to more accurately reflect the true detail parts of an airframe, the existing parts list being somewhat generalized. For example, the detail parts of all the lifting surface box structures are assumed to be the same, and in actuality most closely represent a typical vertical stabilizer. A modified approach would analyze the parts for each lifting surface separately. In particular the interface between the box structure and the various control surfaces and high lift devices could be more accurately represented.

   It is recommended that an analysis of the detail parts be made for the fuselage penalty items – floors, doors, windows, bulkheads, gear wells, etc. The existing program utilizes a statistical approach to these items.

   It is also recommended that additional modes of construction be made available at the detail part level. Currently the program has the capability of analyzing several primary modes of construction through the structural synthesis level, but has corresponding detail parts for only a single mode of construction. The program should be extended to include detail parts for several alternative modes of construction including skin-stringer, multi-spar, and sandwich for the lifting surfaces, and built-up frames and sandwich skins for the fuselage. As part of this refinement the detail parts for the various cover panel types, and spar and rib types discussed earlier would be available. In the existing program the user selects these items as part of the synthesis input, but after leaving the synthesis portion of the program, the analysis reverts to a single configuration mode with a single list of detail parts regardless of the selected configuration.

Another area of suggested improvement is the rib functional-type callout. Presently the program specifies four rib functional types: standard ribs, closing ribs, hinge ribs, and actuator-hinge ribs. However, since there is not at present a corresponding analysis based on rib functional type, all rib types, if sized for the same location, vary in name only. Because the program does contain a logic sequence for placing the various functional-type ribs in certain positions relative to each other, a reasonable next step is to reflect in the part lists and in the sizing procedures the differences between rib types.

h. Weight data was generated in four areas of the program. Overall vehicle system weights were derived as part of the vehicle synthesis; optimum or idealized weights were derived as part of the structural synthesis; and actual and material weights were derived based on the detail part geometry. Weight data output for optimum, actual, and material weights are presented at the detail part level. Summations are made for major component and overall vehicle weight.

i. Standard hour equations were established to estimate the theoretical number of hours necessary to manufacture each detail part. It was shown that it is possible to obtain the type of standard hour data used by engineering planning departments, and to formulate empirical equations based on curve fits of standards data. These equations were shown to have the capability of reproducing the standard hour estimates found on shop planning sheets. By applying appropriate realization factors to the standard hours derived for each operation, it was shown that the corresponding actual labor hours can be estimated. Use of proper direct and overhead rate data then produces values for direct and overhead manufacturing cost.

It is recommended that the standard hour equations be updated and expanded. The current equations were based on dated standards data issued from 1953 to 1961. More complete and more up-to-date information is available, which should be used to establish an updated and expanded shop library of standard hour equations. In particular, the effect of fabricating larger parts, use of numerical control and multi-tool machinery, use of advanced composite fabrication techniques, etc., should be taken into account.

It is also recommended that a sequence of manufacturing processes be assigned to each individual detail part. At present all detail parts are combined into one of 17 generalized manufacturing process sequences. As part of this task the manufacturing process callouts for the detail parts should be checked for accuracy against actual planning sheets.

Also, better methods for deriving and sequencing the assembly operations and the corresponding standard hour computations need to be developed. Currently, a single assembly sequence is utilized for everything from minor subassemblies to final airframe assembly.

In order to incorporate advanced composite materials into the standard hour analysis several limiting assumptions were made. In general, composite materials were assumed to have the same form and structural function as the equivalent

metallic parts. The effect of this is that much of the cost benefit gained in composites by using relatively a smaller number of large parts is not reflected by the present approach. It is suggested that as a refinement to the program an analysis of the actual composite versions of the aircraft detail parts be made. In this way the true impact of an advanced composite mode of structure may be explored.

Also as part of a refinement to improve the analysis of advanced composite structures, an attempt should be made to more closely model the associated fabrication and assembly techniques. The current treatment of composite manufacturing processes is rather simplified due to the limited amount of detail available in historical cost data. For the most part, actual cost data presently available is derived from the fabrication of a small number of handmade parts, and thus lacks a relationship to a production basis. As more cost data detailing typical manufacturing process breakdowns becomes available, a standard hour-type of analysis methodology should be developed and applied.

j. Rate data, including labor rates, overhead ratios, and realization factors, were incorporated into the cost analysis as a function of time. Historical data were studied for various rate categories and equations were derived to compute costs for any specified reference year.

k. A material cost routine was developed that derives the raw material cost based on the following material parameters: material type and form, quantity bought, and various cost extra items such as extra lengths, widths, and special tolerances. Material cost is computed for any specified reference year by utilizing an inflation factor in the cost equations. A single value for the manufacturing usage variance factor was used for all material forms.

It is recommended that a separate value for manufacturing usage variance factor be established for each material form, such as sheet/plate, honeycomb, fasteners, etc. This is particularly important for cost analyses involving advanced composite materials; in this case the material cost is a large fraction of the total cost of manufacturing an item, and hence, strict material controls are applied.

l. A method for deriving an engineering cost breakdown was formulated based on historical data and equations developed by Levenson and Barro. Both initial and sustaining engineering costs are represented.

It is recommended that a future refinement of the program include an analytical treatment of engineering costs at the task requirement level. The capability should be developed to specify typical tasks associated with each engineering discipline and to compute the corresponding hours required to perform each task as a function of the aircraft design details. In this way the engineering costs would be made more sensitive to the actual aircraft configuration being studied.

m. A method for deriving tooling costs was formulated based on the number of dissimilar parts to be manufactured and the aircraft production rate. Basic tooling, rate tooling, and sustaining tooling costs are represented.

It is recommended that a future refinement of the program include an analytical treatment of tooling costs based on the actual tools necessary to produce each part. Methods should be developed to relate the tooling requirements directly to the engineering and manufacturing manhours needed to produce them. In this way, tooling costs would be made more sensitive to the actual aircraft configuration.

n. A mathematical model for computing total vehicle program costs was formulated utilizing primarily the equations and formats developed by Kenyon. Cost elements computed previously by the program are carried across and substituted into the model in place of the CER-type equations. A learning curve approach is applied to the computed first unit cost to compute the cost of subsequent units or production lots. The resultant output provides the user with a complete production cost picture including total flyaway costs and total support costs.

o. A return-on-investment analysis was successfully coupled to the above synthesis and cost analysis routines. The approach utilizes computed values for aircraft performance and cost, together with an input traffic route structure, to compute direct and indirect operating costs, revenues, load factors, profit, fleet size, and return on investment.

p. Because of the large amount of development and computer debugging time required during the formulation of this program, only a limited number of test cases were run. It should be realized that in order to establish a high degree of confidence in any new program intended for use as an everyday tool, a large number of test cases must be run, checked, and documented. Only in this way can the program be completely debugged and refined for maximum reliability and accuracy. It is therefore recommended that many test cases be run with the program using actual data with known values for weight and cost. In this way the program can be adjusted and refined, and any limiting characteristics exposed and resolved.

BIBLIOGRAPHY

1. Trelease, R. H., et al, Estimation of Airframe Manufacturing Costs, Convair Aerospace Report GDCA-BJF71-918, July 1972.

2. Bachman, W., Geometry and Weight Synthesis Adapted for Use in the Combat Aircraft Synthesis Program, Convair Aerospace Report GDC-ERR-1572, December 1970.

3. Reed, T. F., WTSIZ-Interactive Graphics Program for Aircraft Weight Sizing, Convair Aerospace Report GDC-ERR-1644, December 1971.

4. Caddell, W. E., The Use of Aircraft Density in Preliminary Design, SAWE Paper 813, 1970.

5. Green, G. G., Derivation of a Formula for Estimating Wing Weight, Convair Aerospace Report ZW-018, 1974.

6. Caddell, W. E., Generalized Weight Estimating Methods for Aircraft Structures and Equipment, Convair Aerospace Report GEC-ERR-ZW-039, 1960.

7. Reed, T. F., Karll, M. P., BALSIZ - Interactive Graphics Program for Aircraft Sizing and Balance, Convair Aerospace Report GDCA-ERR-1736, December 1972.

8. Peterson, L. M., Synthesis of Primary Box Components, Convair Aerospace Report GDC-ERR-1525, December 1970.

9. Bruhn, E. F., Analysis and Design of Flight Vehicle Structures, Tri-State Offset Company, Cincinnati, Ohio, 1965.

10. Kruse, G. S., Peterson, L. M., Automated Structural Sizing Techniques for Aircraft and Vehicle Structures, GDCA-ERR-1748, December 1972.

11. Shanley, F. R., Weight-Strength Analysis of Aircraft Structures, Dover Publications, March 1970.

12. Roland, H. L., Neben, R. E., Aircraft Structural Weight Estimation Methods, Convair Aerospace Report GDC-ERR-242, September 1964 (Revised Sept. 1965).

13. Levenson, G. S., Barro, J. M., Cost Estimating Relationships for Aircraft Airframes, Rand Report RM-4845-PR (Abridged), May 1966.

14. Study of the Application of Advanced Technologies to Long Range Transport Aircraft, NASA Report CR 112090, May 1972.

15. Kenyon, R. E., Techniques for Estimating Weapon System Structural Costs, Air Force Report AFFDL-TR-71-74, April 1972.

16. Benson, R. L., Seiden, E. I., Cost Element Research, Convair Aerospace Report GDC-ERR-1379, December 1967.

17. Preliminary Weight and Cost Estimates for Transport Aircraft Composite Structural Design Concepts, NASA Report CR-112255, March 1973.

18. Standard Method of Estimating Comparative Direct Operating Costs of Turbine Power Aircraft, Air Transport Association of America, December 1967.

19. A Proposed Standard Method for Calculating Airline Indirect Operating Costs, Lockheed Aircraft Corporation Report LW-70-500R, May 1970.

20. Kuhn, P., Peterson, J., and Levin, L., A Summary of Diagonal Tension Part 1 - Methods of Analysis, NACA TN 2661, May 1966.

 ~~K. A. Eberhard 245/32/24570~~

 ~~C. Carnhart 245/33/5/32511~~

GENERAL DYNAMICS

Convair Aerospace Division